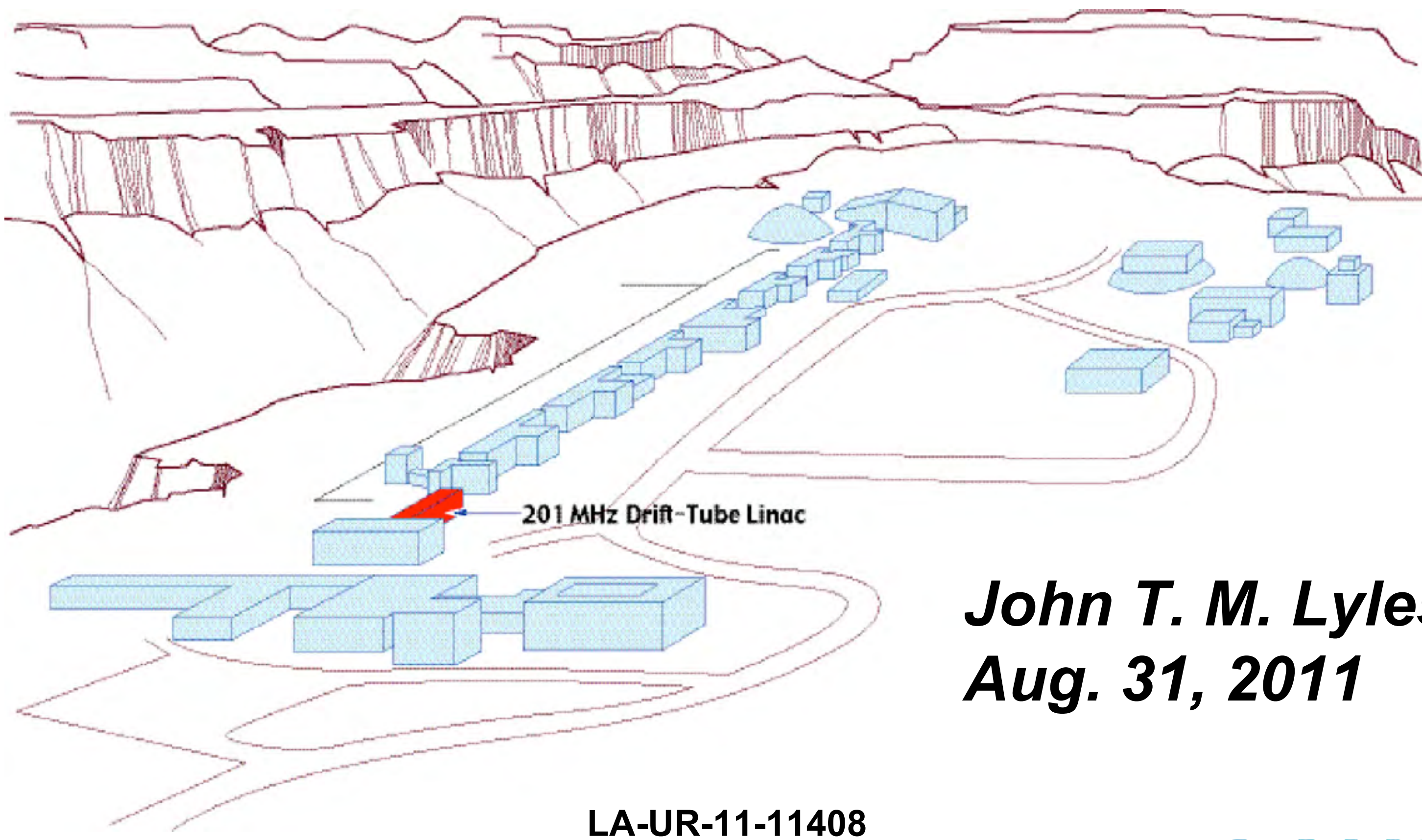
Design and Operating Results

New 201 MHz Radio Frequency Power System for LANSCE



John T. M. Lyles

Aug. 31, 2011

LA-UR-11-11408

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LANSCE Los Alamos Neutron Science Center

LANSCE Drift Tube Linac

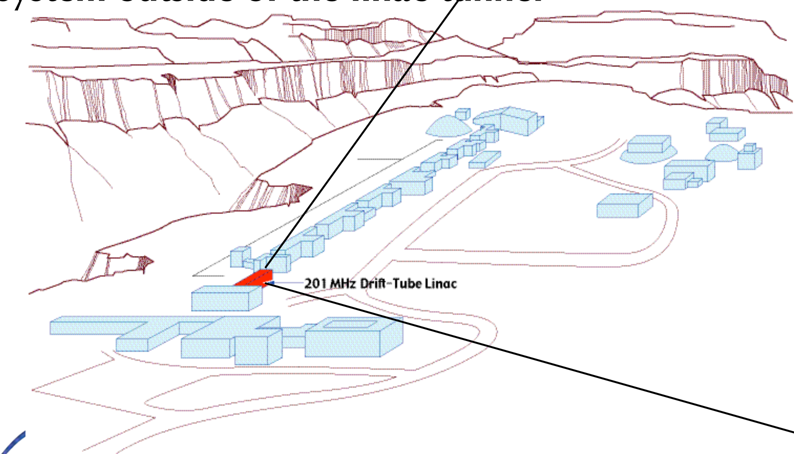
Drift Tube Linac (DTL) occupies the first 200 feet of the 2500 foot LANSCE linac

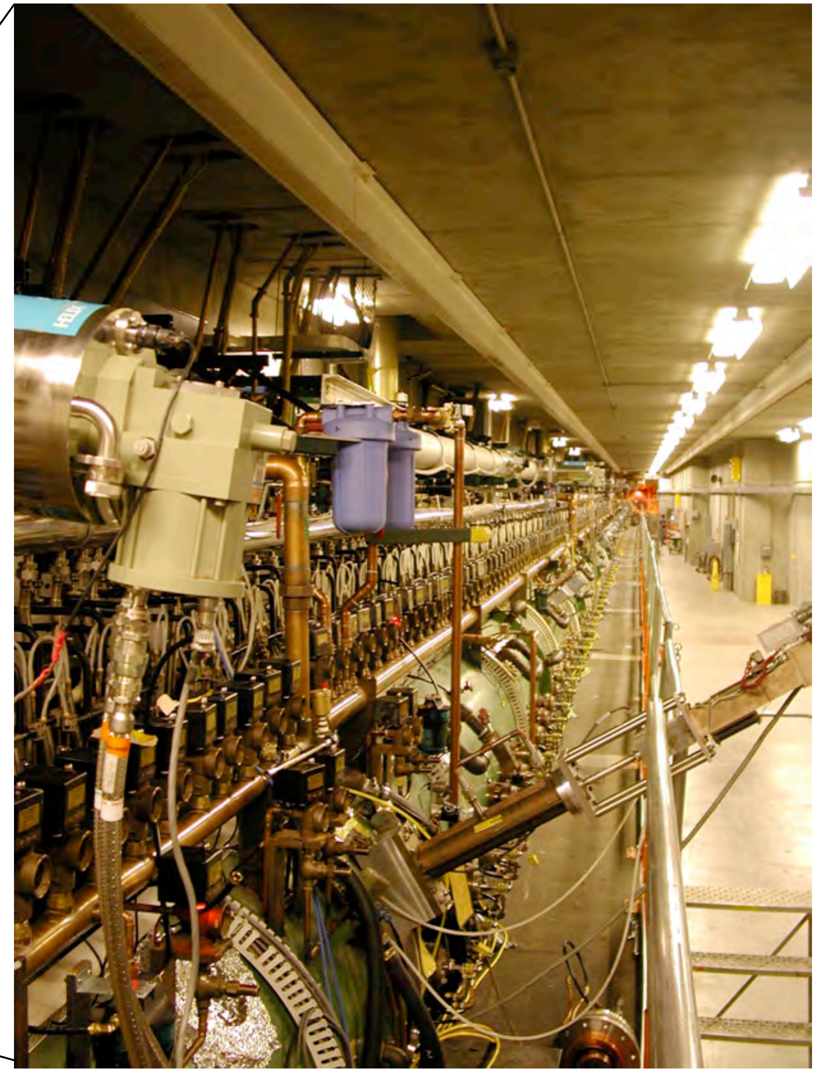
Designed/installed in 1967-1968

Operated as LAMPF for almost 30 years

H+ and H- Protons accelerated from 0.75 to 100 MeV in four tanks, then transferred to coupled-cavity linac at b= 0.428

DTL receives pulses of 201.25 MHz RF power via 14 inch diameter coaxial transmission lines from 4 RF system outside of the linac tunnel





DTL RF Power Requirements

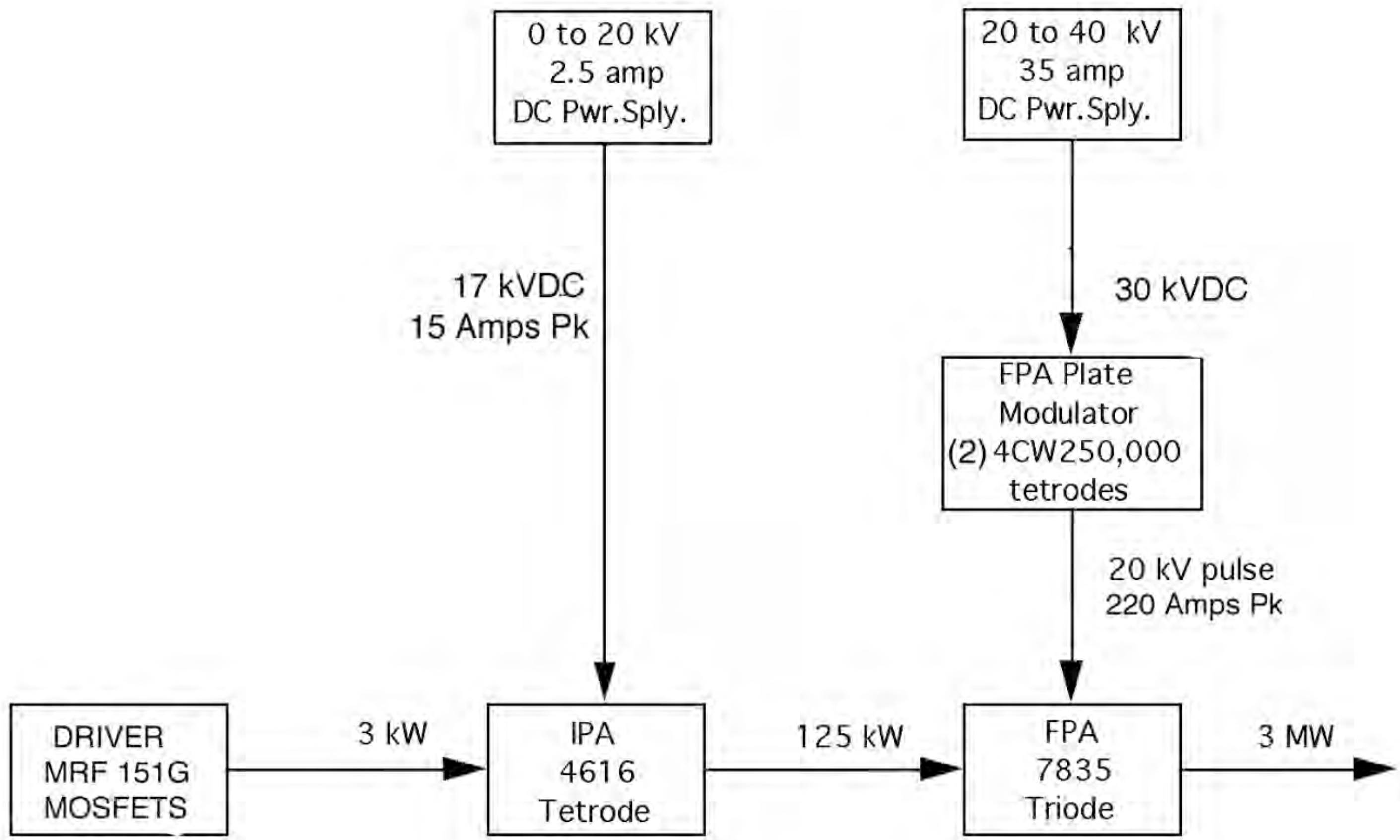
All Peak Powers in Megawatts

DTL Tank	Energy gain	P_{tank}	$P_{+13\ mA}$	$P_{+18\ mA}$	$P_{+21\ mA}$
1	4.64 MeV	0.37	0.430	0.454	0.467
2	35.94 MeV	2.57	3.037	3.217	3.325
3	31.39 MeV	2.10	2.508	2.665	2.759
4	27.28 MeV	2.23	2.584	2.721	2.803

- Tank 2 needs the highest power, and the RF amplifier suffers highest downtime from tube problems

- Future requirement for MTS, MARIE, want 2 MW beam power; therefore, goal is 3.6 MW for amplifiers for modules 2-4

Present RF System



Background - 200 MHz RF Tube

Burle 7835 Triode

- 7835 has a circular array of 96 grid-cathode assemblies, each with 70 Amps of DC filament current
- Double-ended tube, for higher power at higher frequency (see next slide)
- Rated for 300 kW of anode dissipation, RCA recommended less
- LANL sets calorimetric/hardware limits at 250 kW due to increased fractured ceramic seals.
- 7835 and 4616 were designed ~ 53 years ago
- 7835 contains a large number of intricate parts; manufacturing process labor intensive with skilled workers. Original engineering staff retired
- There is no RF test provided. It is up to the labs to accomplish this time consuming job, which takes a month - to many months for a difficult tube
- LANL has the most trouble with duty-factor (thermal) related problems
- In 2005 reduced overall DF by half (6% now) due to tube emission failures related to gas, Burle unable to solve problem

Double-Ended RF Circuit in 7835

The double ended configuration requires a "slave" cavity on one end of both the input and output terminals. The function of the slave cavity is to reflect a voltage standing-wave maximum to the center of the active region within the tube.

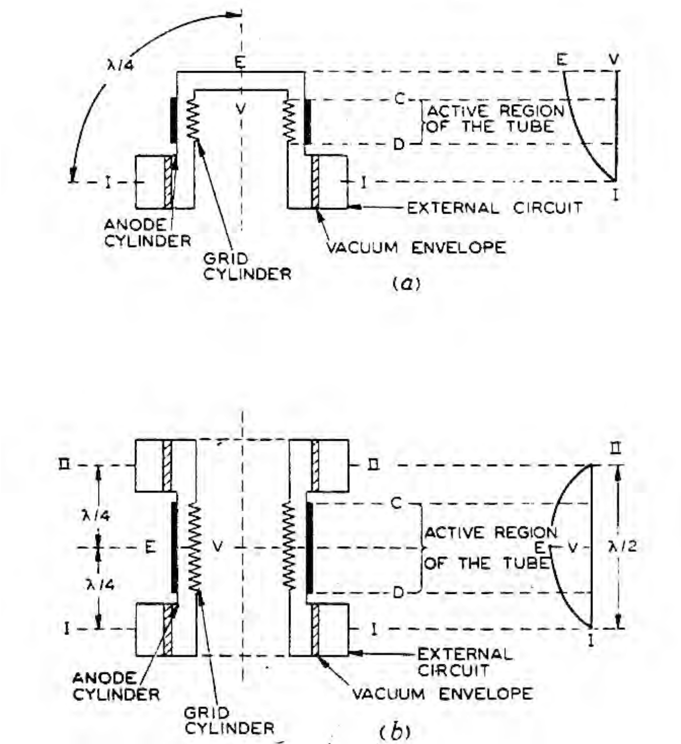
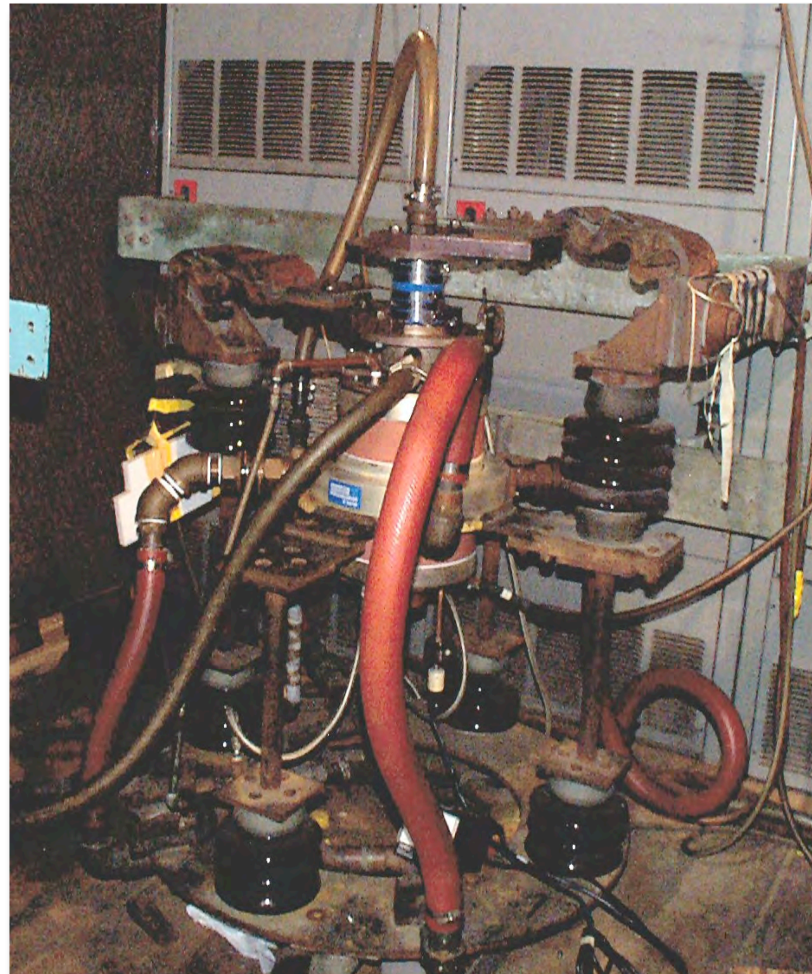


Fig. 1.—Simple longitudinal cross-section of the output circuit for triode: (*a*) in 'single-ended' arrangement; (*b*) in 'double-ended' arrangement.

Source: Hoover, "Advances in the Techniques and Applications of Very High Power Grid-Controlled Tubes", IEE paper 2752R, Nov. 1958

“Potty Chair” at Burle Industries

- This is the only powered test performed for the 7835, using DC power supplies to determine integrity of vacuum
- FNAL, BNL and LANL donated enough spare equipment (without manpower) to make a high power RF system
- For 10 years there was little progress
- Most of this equipment was returned to the labs when Photonis bought Burle



Reasons to Replace RF System

- Return to full beam power by raising duty factor back to 12%, providing more beam time to users

- Eliminate troublesome high level anode modulation, while saving 540kW

- Reduce number of tubes at DTL from 24 to 10, with only 2 types

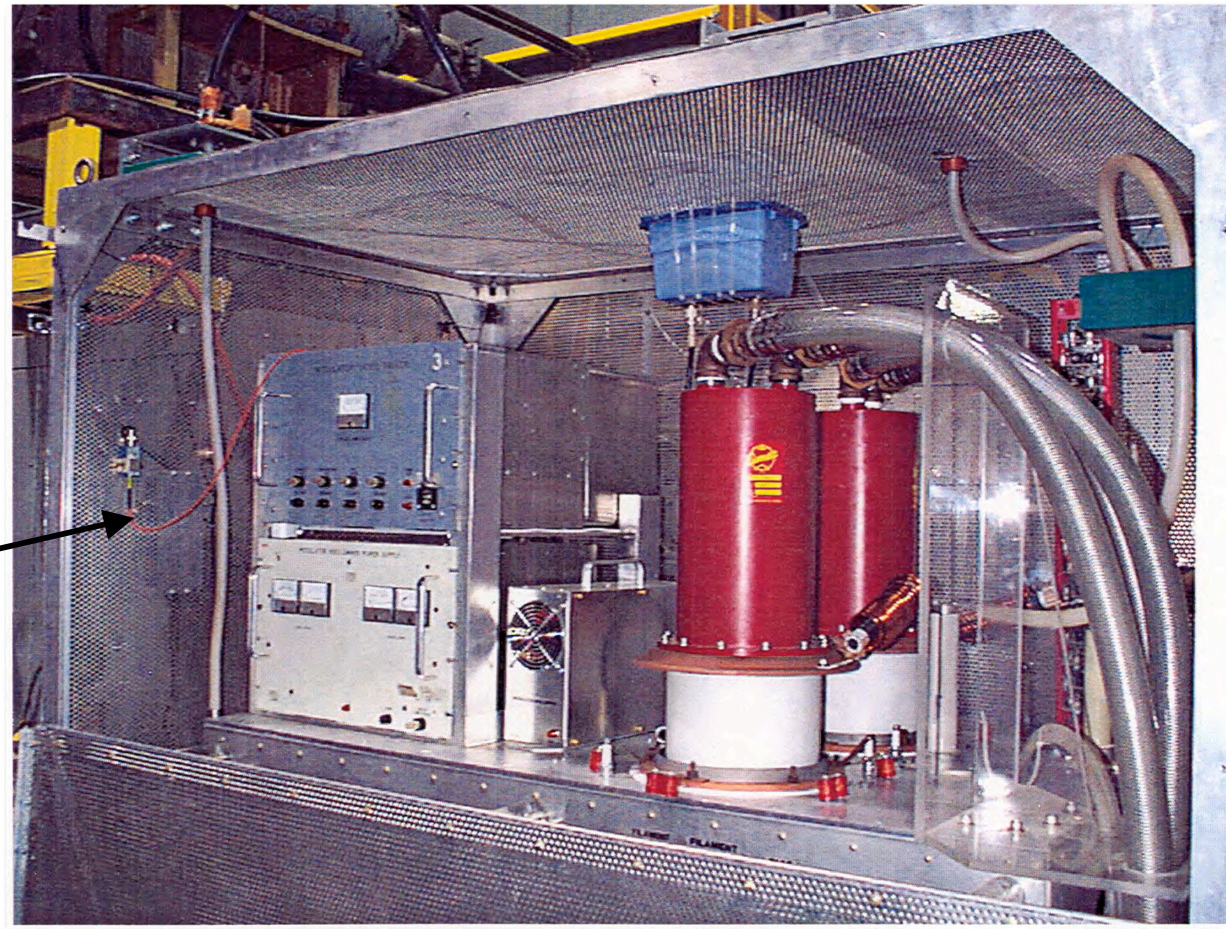
- Non-pressurized amplifier with quicker tube change time (2 hours versus 14 for 7835)

- Replace obsolete amplitude/phase controls with low level I/Q modulation with setpoints tailored for each species, reducing losses

- Provide headroom to accommodate future proton beams > 1 MW

Anode HV Modulator for Each FPA

- Uses 4 Vacuum Tubes
- Typically Lasts 30K Hours, except for driver tube
- $27-52K Tube Replacement
- Dissipates ~180kW Heat into Water System x 3
- Requires 10 kV capacitor voltage overhead over 7835 voltage
- Nonlinearity of f/o Coupling Affects Amplitude Control Loop
- Propagation Delay Limits Bandwidth of Control Loop
- Isolation Transformers Require Flammable Oil, Not Sealed



TH628 Diacrode

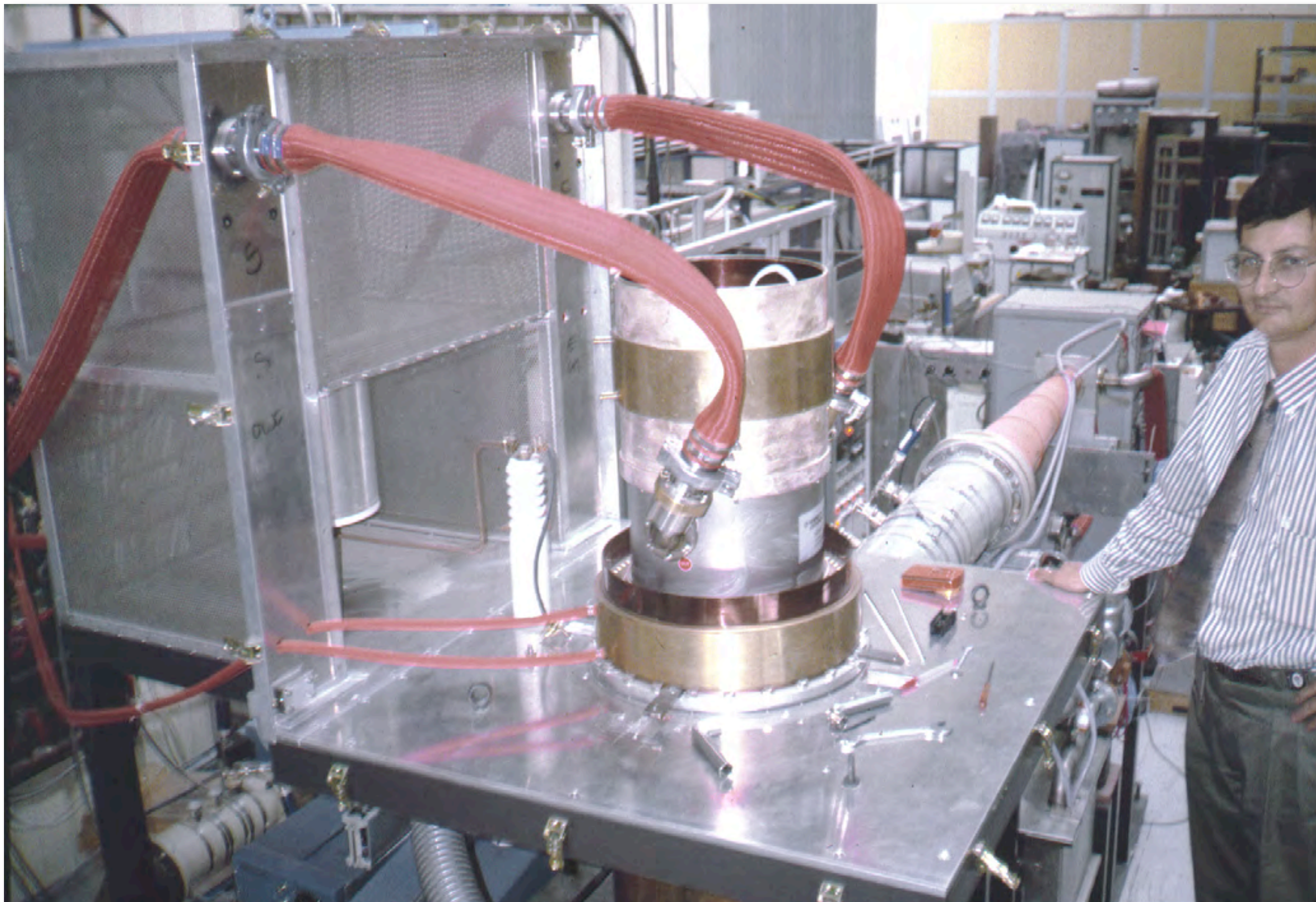
- Developed by Thomsom Tubes Electroniques in early 1990s
- Original target market was ICRH (fusion) heating, 1 MW CW power
  - Pyrolytic graphite grids
    - Can be operated at much higher temperatures with low secondary emission
    - Can be manufactured using modern computer-controlled cutting processes, not like hand-wound wire grids.
  - Multiphase cooled anode
    - Can dissipate much higher power densities with less water, using the latent heat of vaporization
  - Double-ended tube (like 7835)
    - In a typical case, the voltage varies 8% over the active region rather than 36% and the maximum current density is reduced to half of a single-ended tube. Doubles power and improves DC to RF conversion efficiency and power gain

Evolution of Diacrode

TH526 Fusion Tetrode --> TH628 Fusion/Linac Diacrode

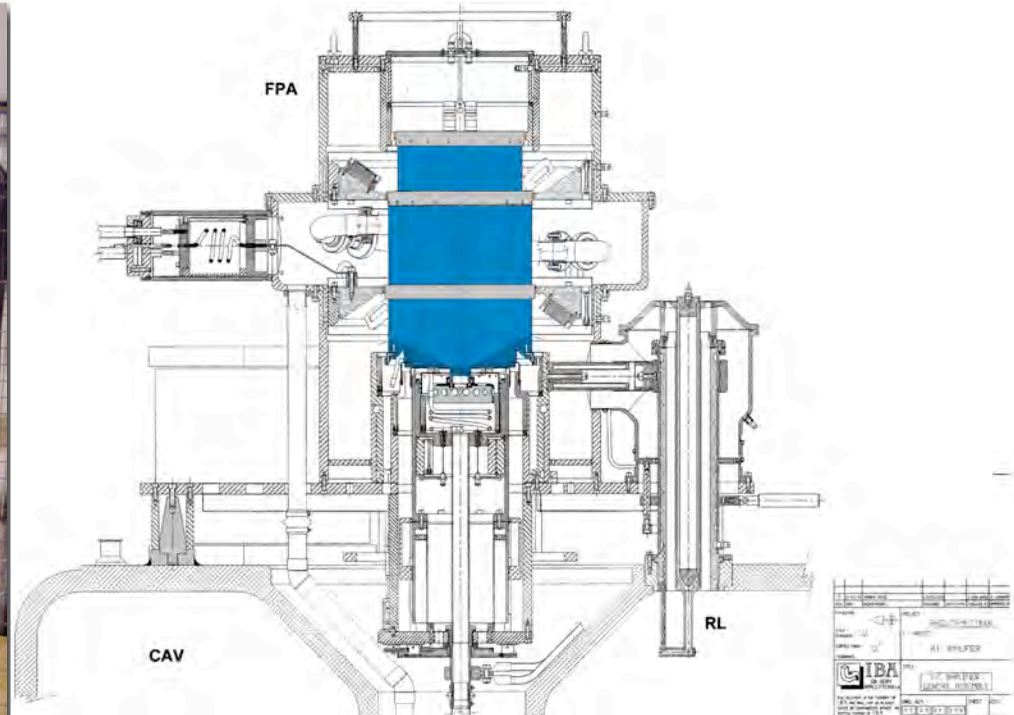
2 x f_{max} and 2 x P_{max}

Testing Developmental D28 at Thonon les Bains,1993



Comparison of 7835 and TH628

IBA Using TH628 at 1MW CW



Rhodatron E-Beam machine for sterilization, industrial applications, at 107 MHz

Ionization Cooling Test Facility

CERN leading design study of Diacrode as RF driver

D7.4	RF_Ampl-DR	Design report of a 3 MW power amplifier	Report	CERN	36

WP7 Milestones

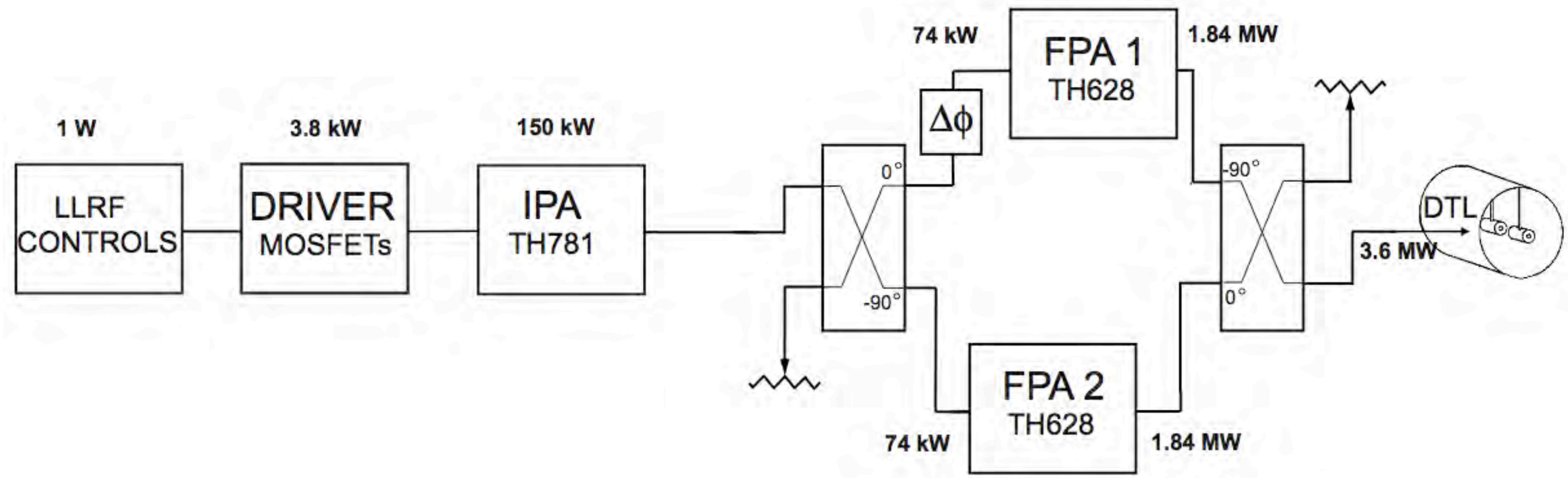
Nb	Name	Description	Type	Lead beneficiary	Planned month
MS27	RFSysReq	Report on RF system layout and requirements	Report	STFC	8
MS28	SymDiac	Simulation of Diacrode complete	Report	CERN	19

Development of New RF System

TH628 Diacrode

- With 3.6 MW and 12% DF planned, we would be operating above the screen grid rating of a single TH628
- 2010 ES&H requirements at Thales forced change in pyrolytic graphite treatment that used silane/borane gas for doping to reduce RF loss; this required further derating of new tube
  - Combining two amplifiers at DTL2, 3 and 4 solved both
- Each TH628 will be operating at 150 kW anode dissipation or 19% of rating, instead of 90% as with the 7835 triode
- Cathode emission requirement reduced due to larger emission area (800 versus 300 cm^2) and lower peak current
  - 3 amps/cm^2 in 7835 and 1 amp/cm^2 in TH628 = significant lifetime improvement predicted, can reduce filament temperature

New RF Power System



Cost Comparison

- Untested 7835V4 costs $227K without extended warranty, as warranty is worthless to LANL; dispensation of every tube failure is negotiated case by case with Burle Industries. Rebuilds beyond R2 have shorter life at LANL and are uneconomical.
- Full power tested TH628 costs $240K, 200 hour full warranty and 4800 hour prorata, for 24 month period; no extended conditioning time needed at LANL
- Cost of second tube doubles purchase cost initially. Lifetime for TH628 with reduced filament emission requirement and lower electrode dissipation expected to be longer, estimated 20-30K hours.
- Cost of combiner, splitter, second power amplifier, etc. doubles initial capital cost
  - Use same capacitor bank and charging power supply
  - Remove anode modulator
  - Water cooling for two TH628 same as one 7835
  - TH628 power efficiency DC to RF is >65%, with 7835/modulator is 40%

Acceptance Test - First Production TH628 in Thonon, 1998

Met all LANL criteria, including 3 MW at 20%DF

Retest same TH628 in Thonon, 2007

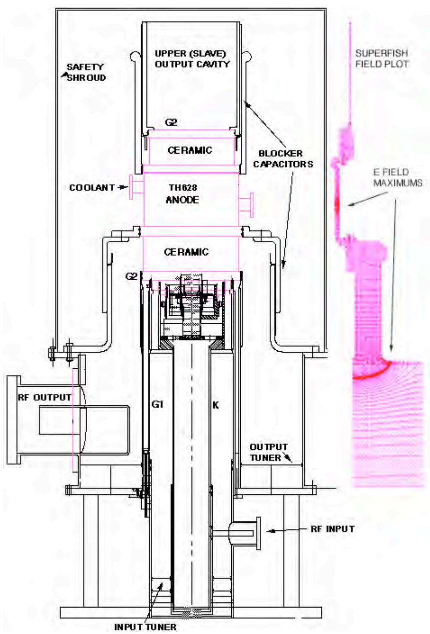
Why?

- Uncertain of vacuum condition after 9 years in crate at LANL
- Operated at 800 kW anode dissipation without RF drive, after few hours of warm-up
- Ran 3 MW, 20% DF
- Arced dummy load twice, test finished
- Tube returned to LANL, excellent vacuum and very strong

Final Power Amplifier

Evolution:

Mk I - cold model 2000 **Mk II - 2010**



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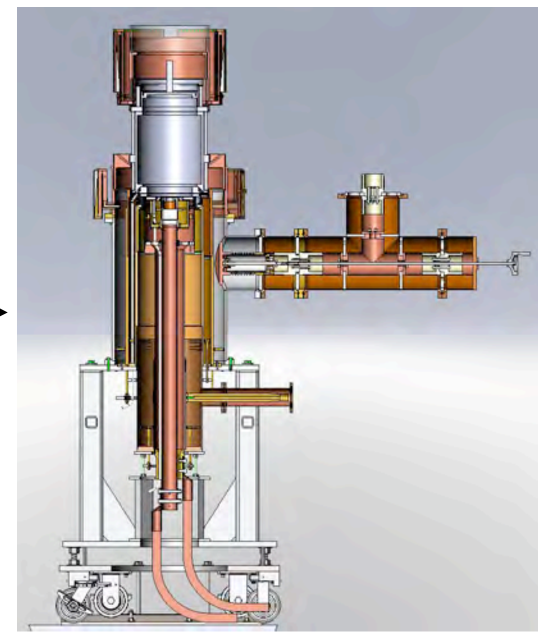
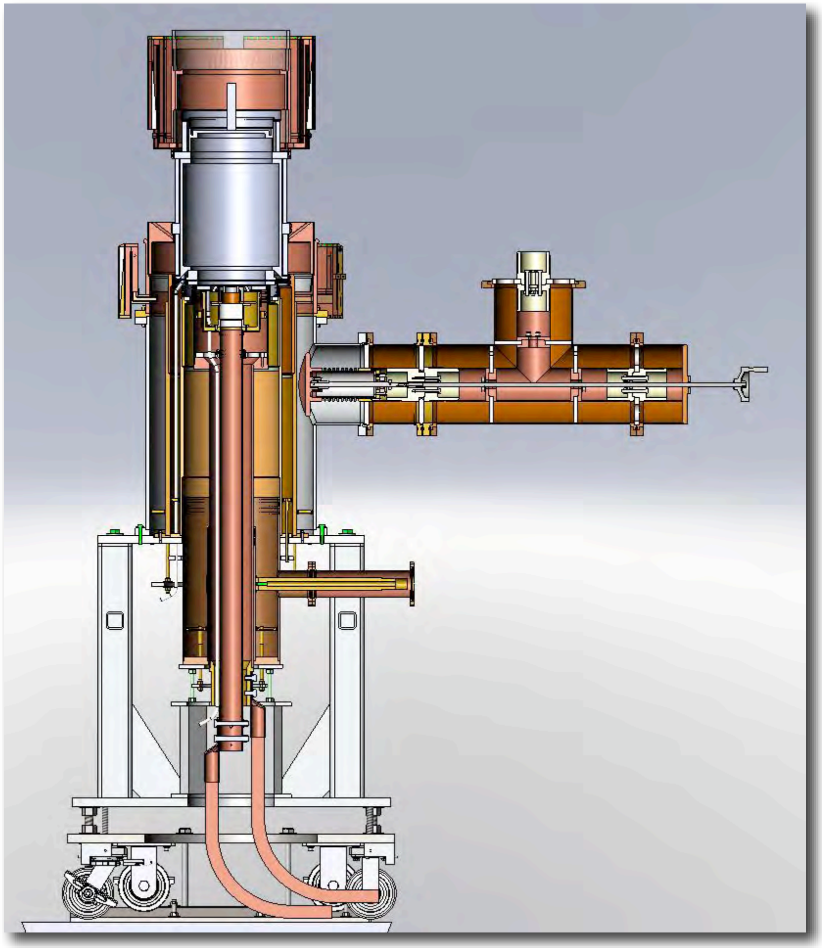
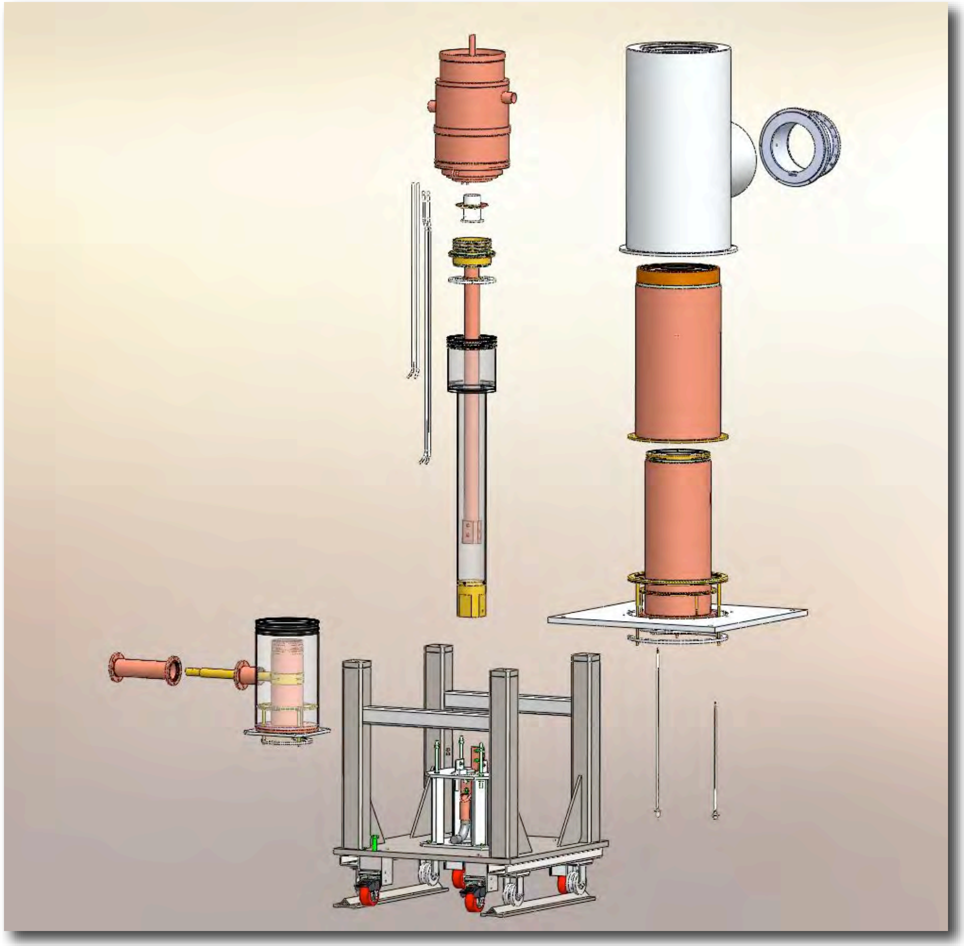


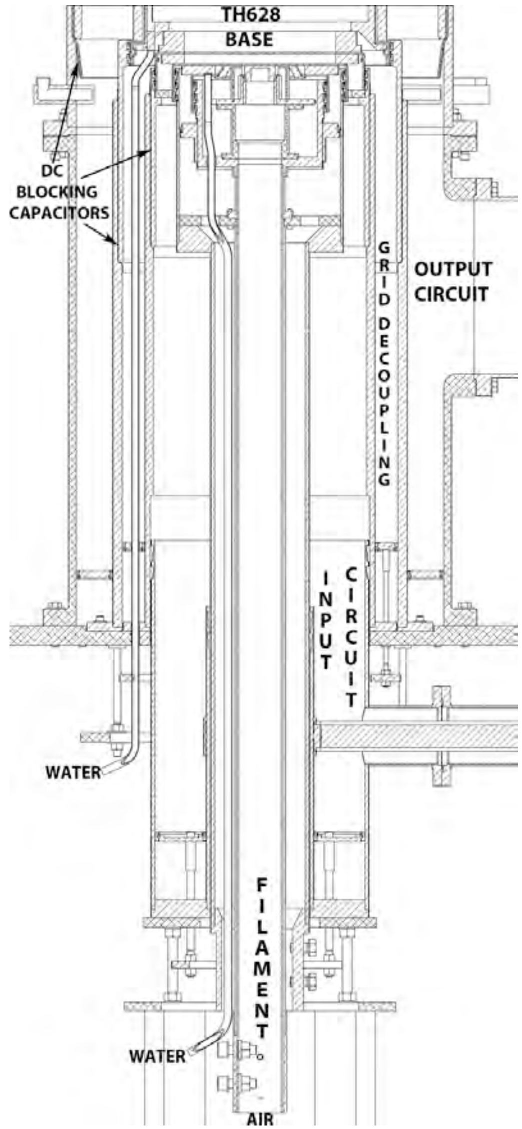
Superfish and Fortran Transmission Line Code Optimization

Final Power Amplifier





Lower Circuits



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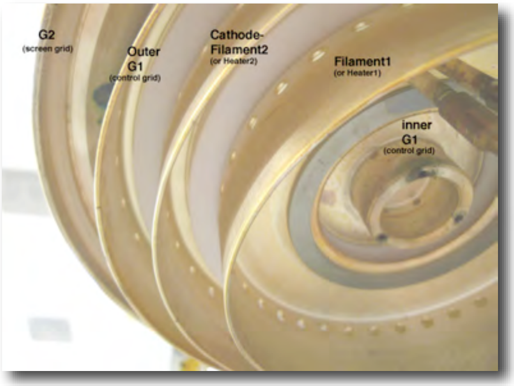
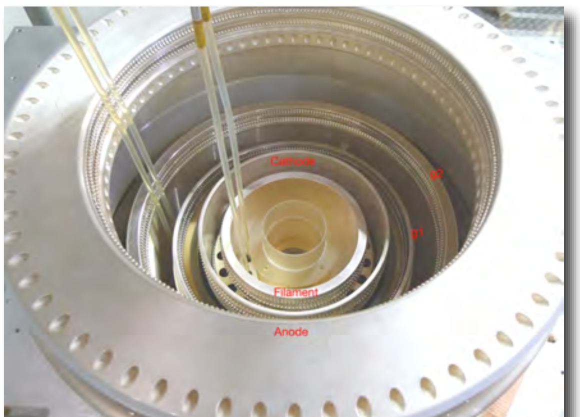
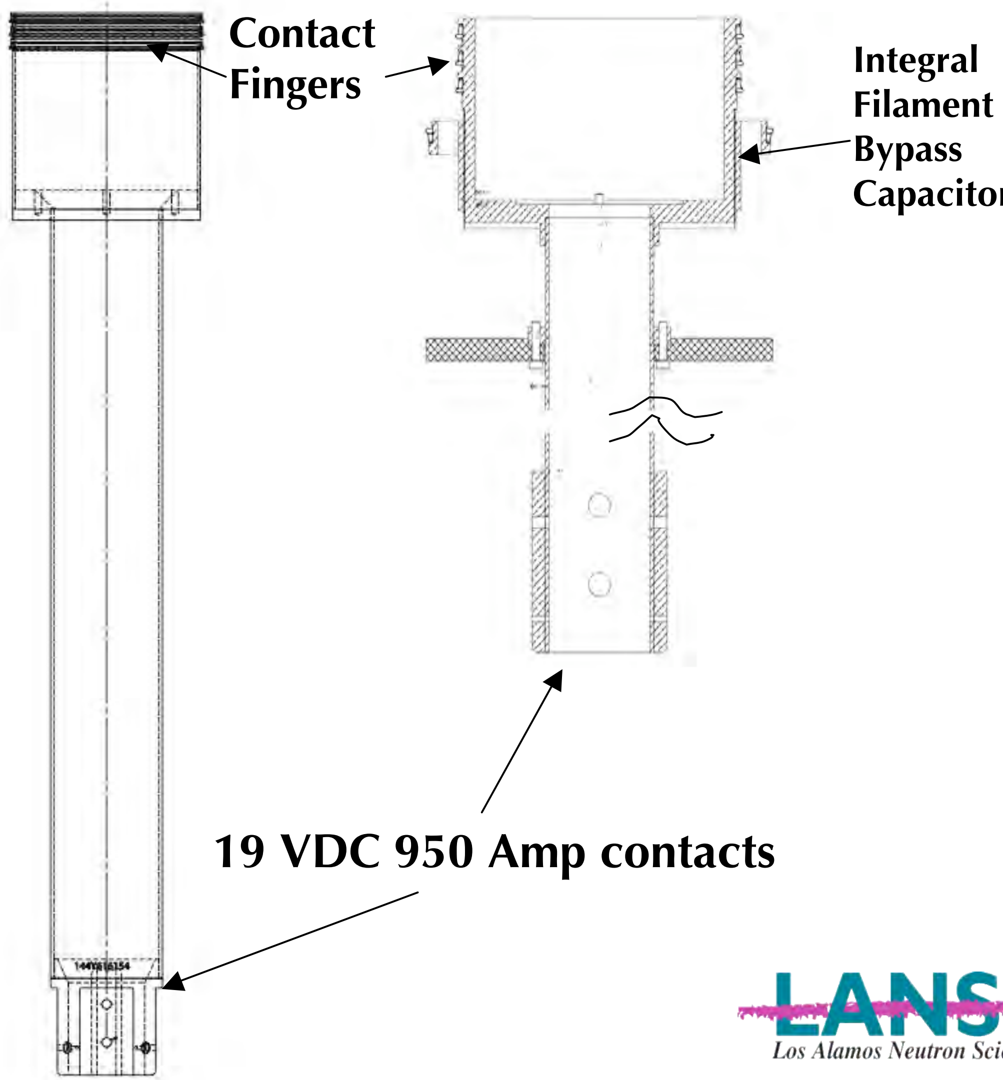
FPA Input Circuit

Heater/Cathode Lines







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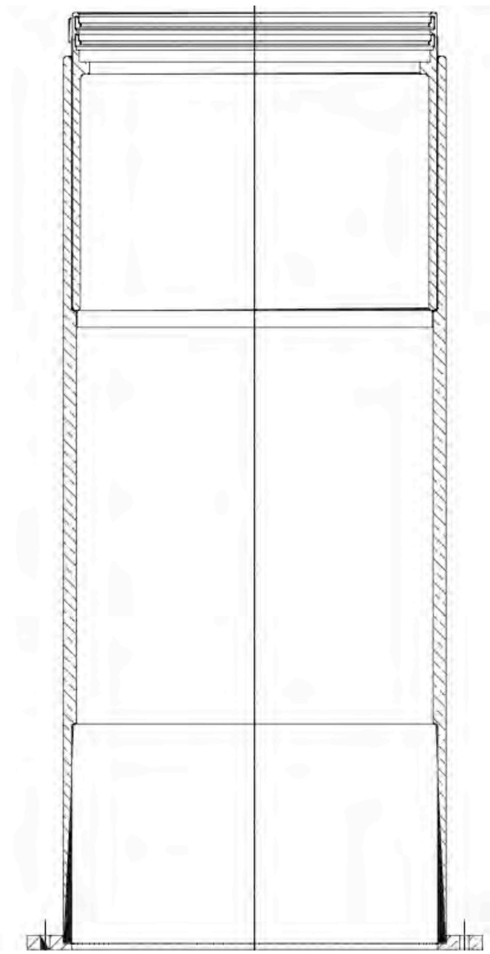
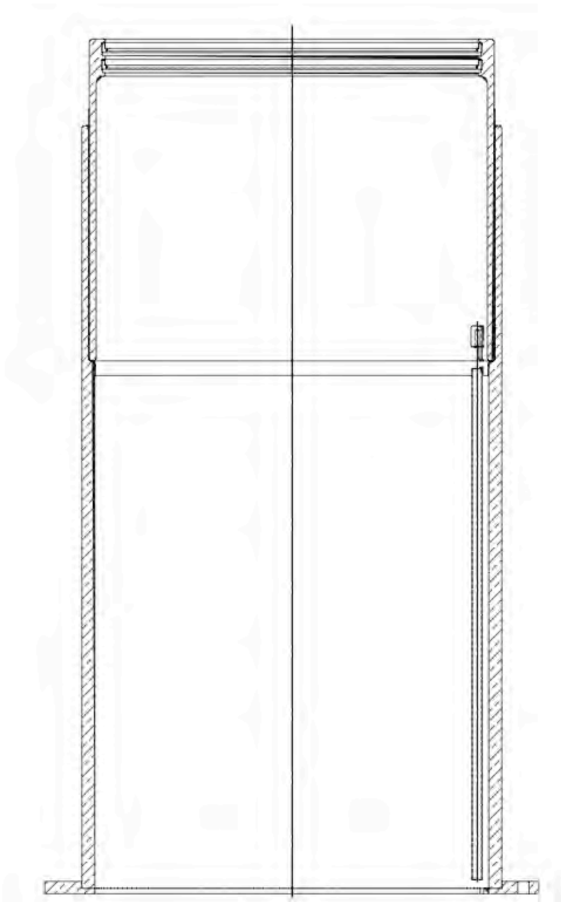
FPA Input Circuit

G_1 Line/DC Blocking Capacitor



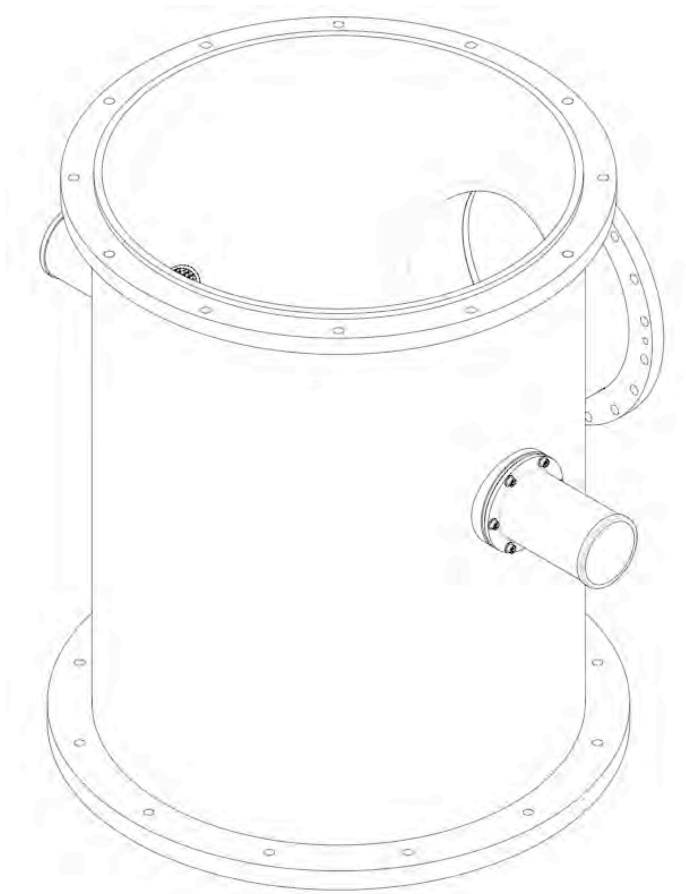
FPA Output Circuit

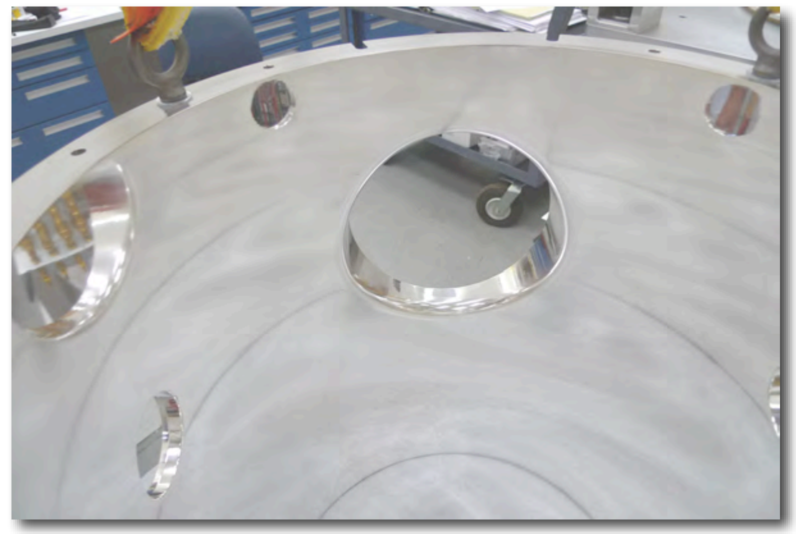
G_2 Line/DC Blocking Capacitor



1 Layer 0.02″ FEP film
Interference fit at room temperature
Capacitor is 80 nF, 6 kV

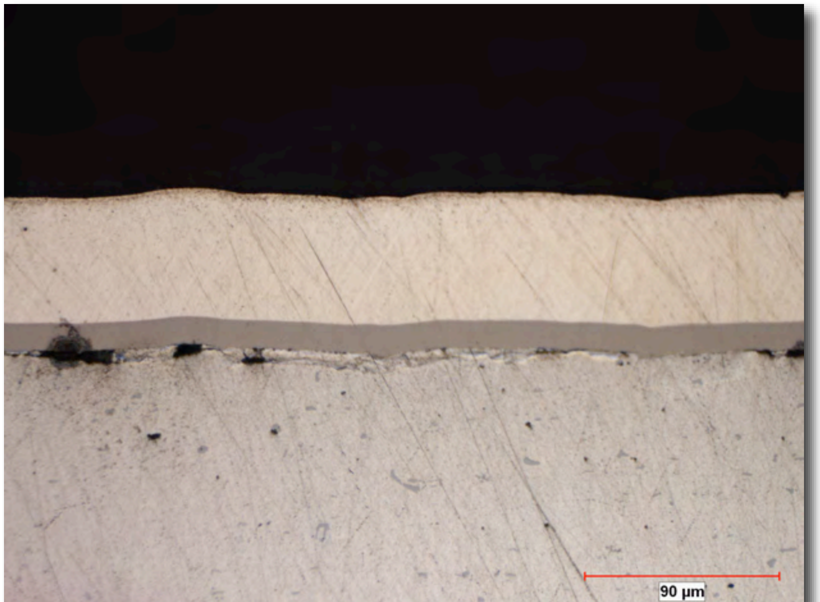
FPA Output Circuit



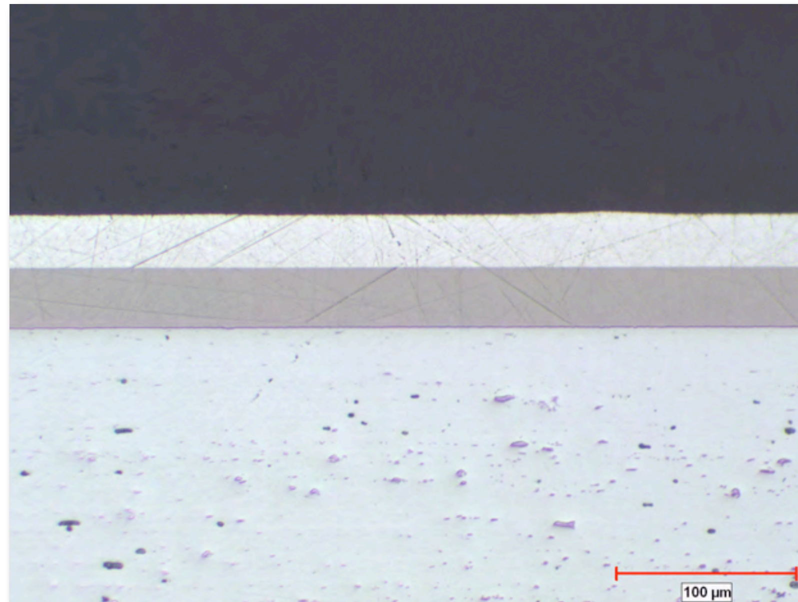


Aluminum Outer Shell 65 lbs.
Electroplate Ni + 0.0006″ Ag
Production units will be copper

FPA Output Circuit Plating



Initial test, Plater #1

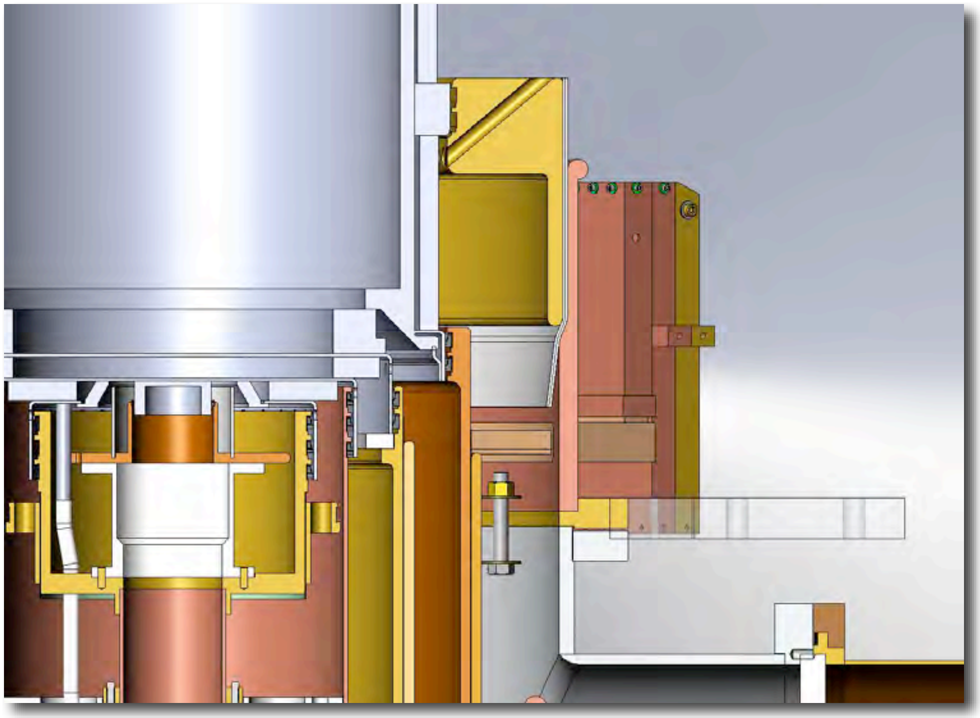


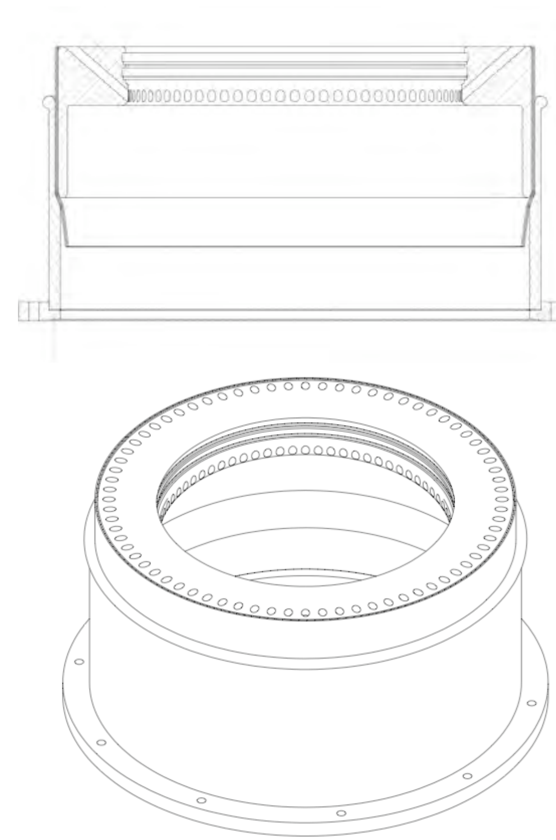
Plater #2

Learning curve was steep but solutions were found

FPA Output Circuit

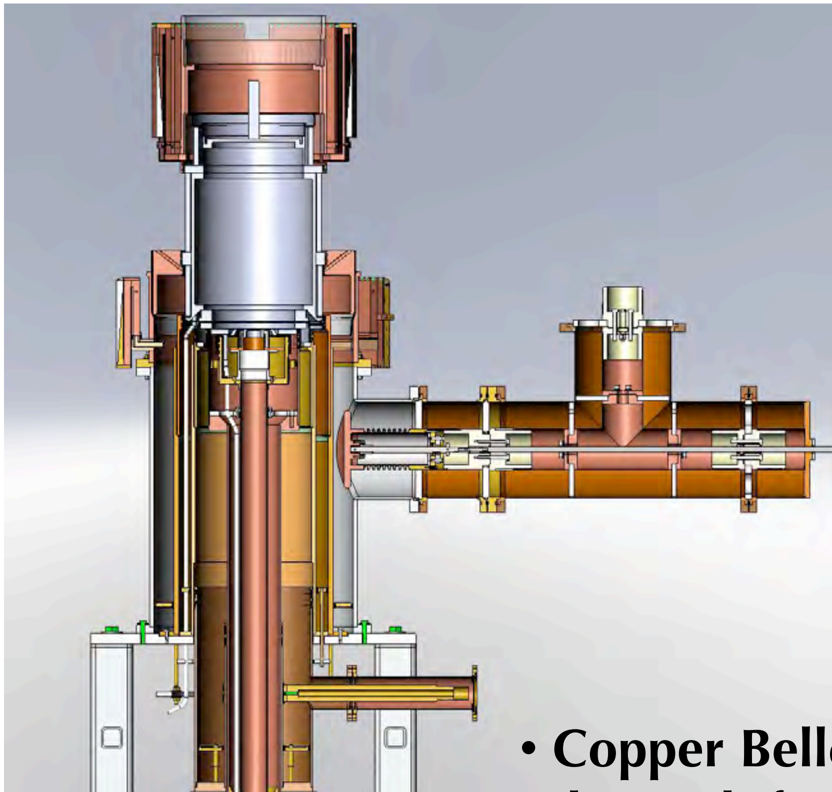
Anode DC Blocking Capacitor Design

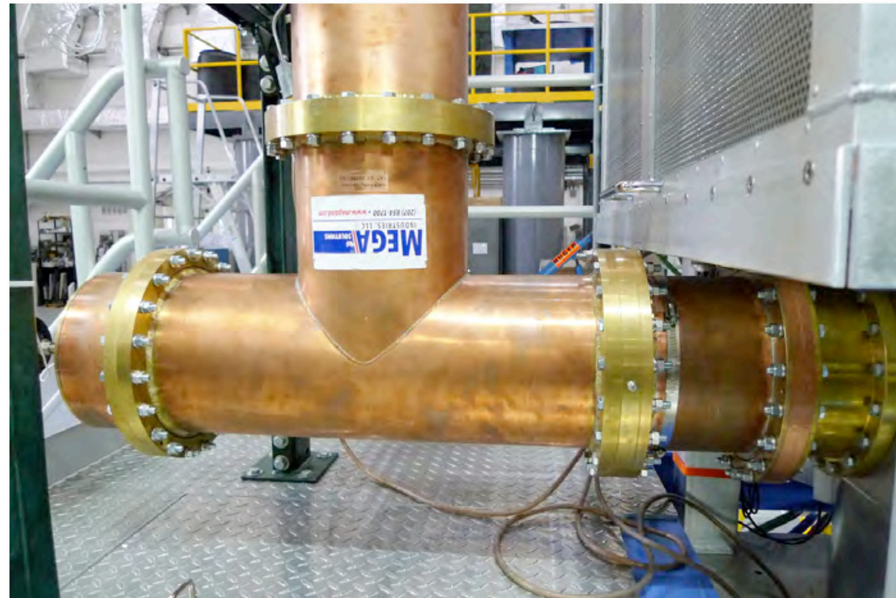


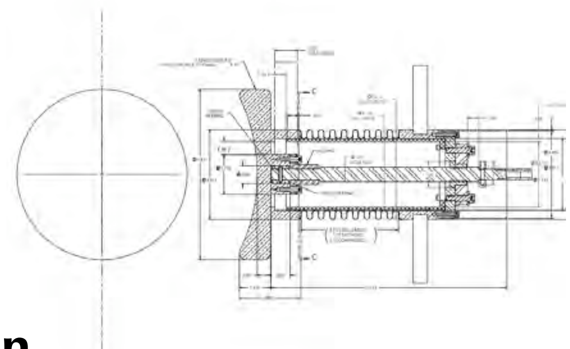


2 Layers of 0.06″ FEP
Interference Fit at Room Temp
750 pF, 60 kV DC, λ/8 length

Capacitive Output Coupler







- Copper Bellows
- l/4 Stub for Mechanism
- Easily Removable
- Adjustable Under Power
- Second harmonic suppression

High Order Modes

• Generated in annular region between screen grid and anode by electron stream at discrete voltages and electron densities

• Large diameter radial beam gridded tubes show tendency for UHF and L Band HOM

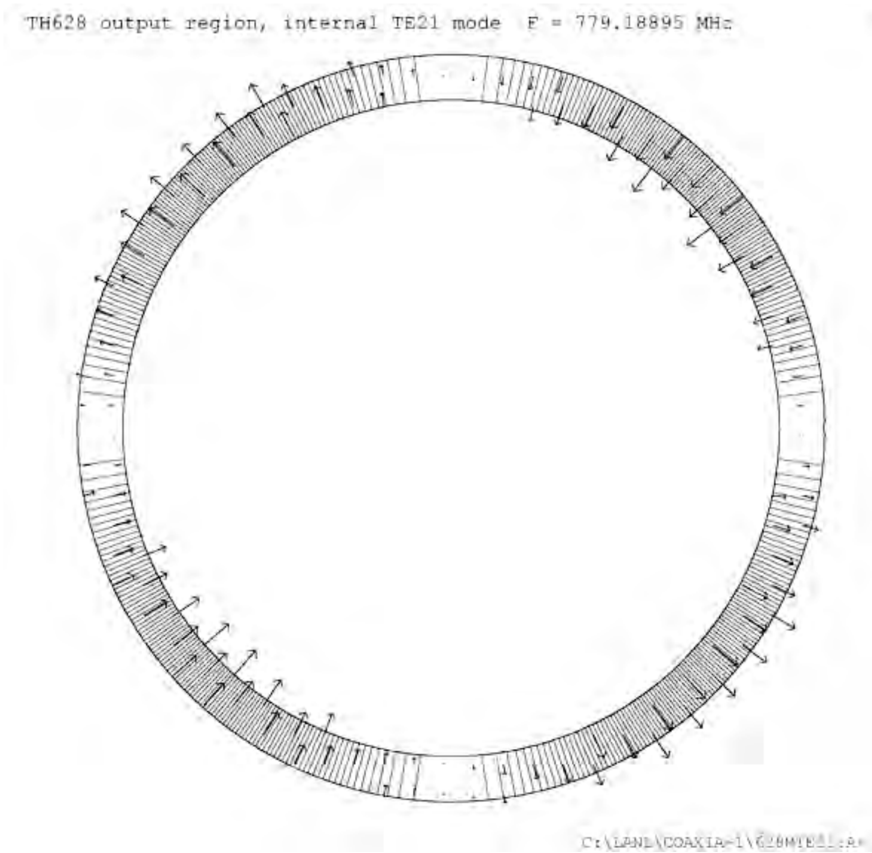
• Conventional large tubes have damper material inside top area

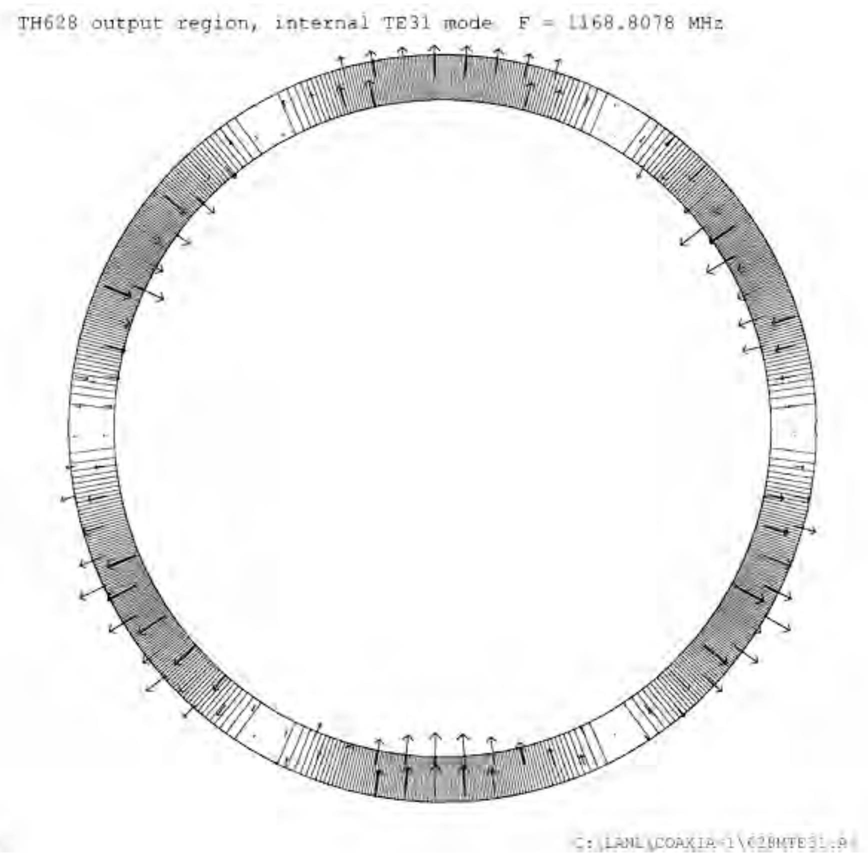
• Double-ended TH628 and 7835 have active connections at top so cannot dampen internally

•7835 solution - Switch HV off between RF pulses and always saturate drive, costly, poor linearity so use high level modulation

•TH628 solution - passive dampers in amplifier circuit that are non-intercepting with 201MHz

Transverse Electric Field Modes
Predicted from Superfish





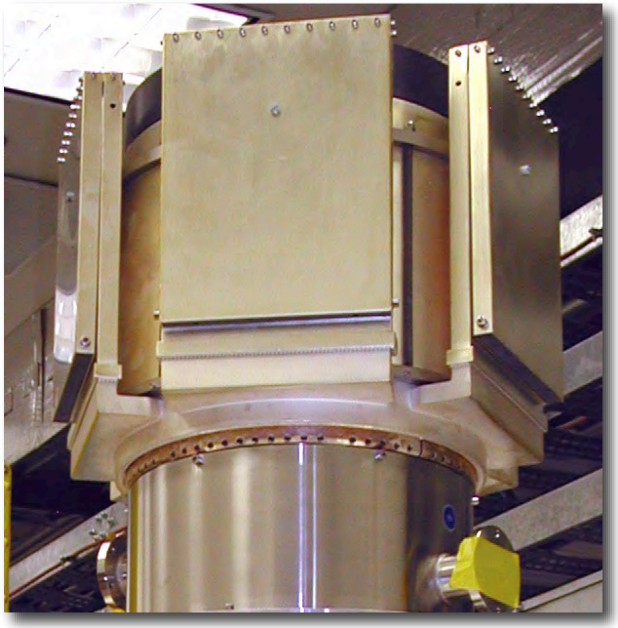
ID is Screen Grid (G_2), OD is Anode Cylinder

TE_{31} at RF Turn Off

1.28 GHz Burst

Anode Current

HOM Dampers

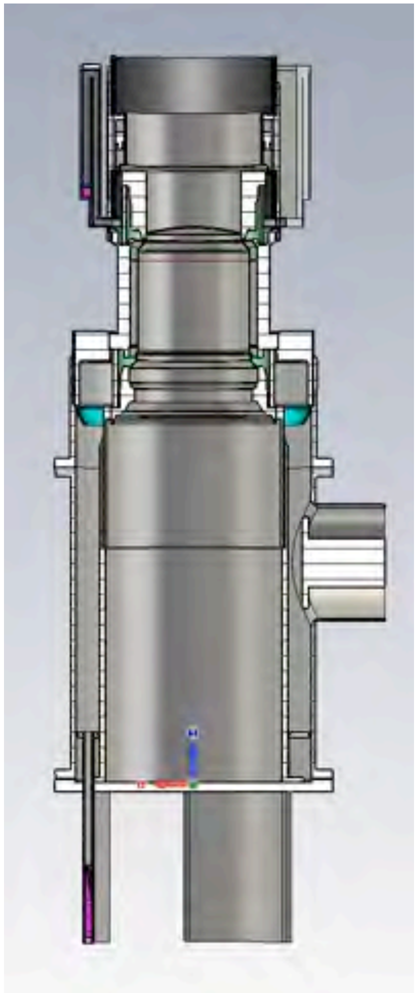


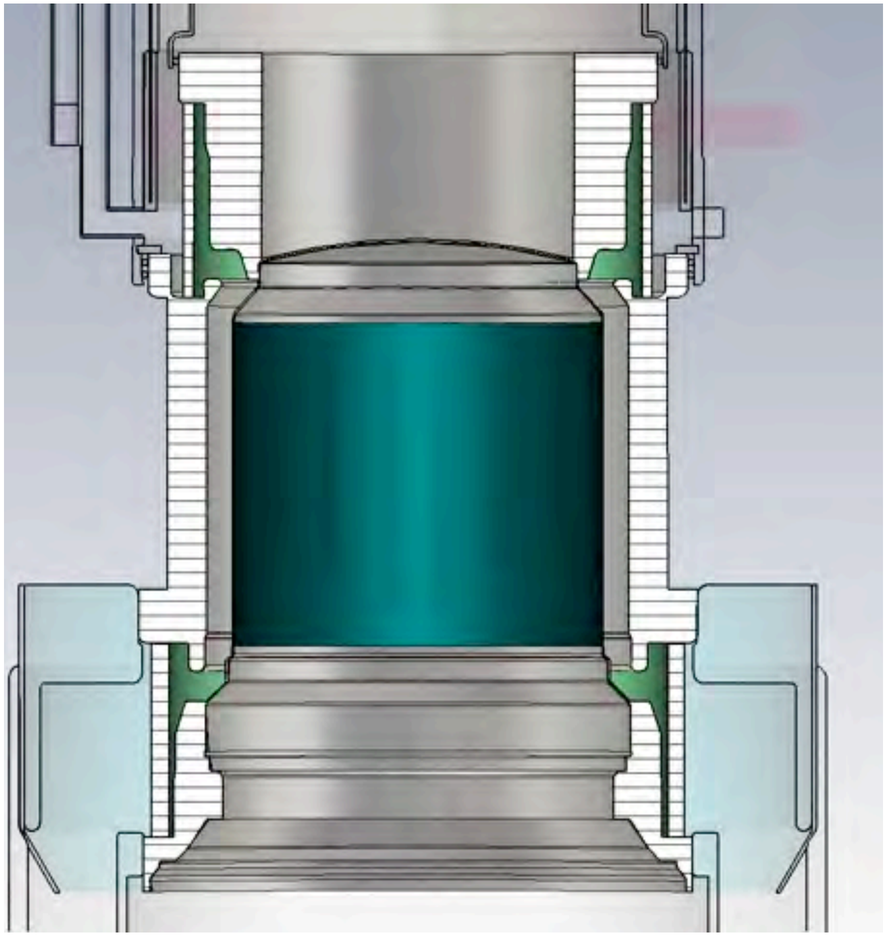
Upper

Lower

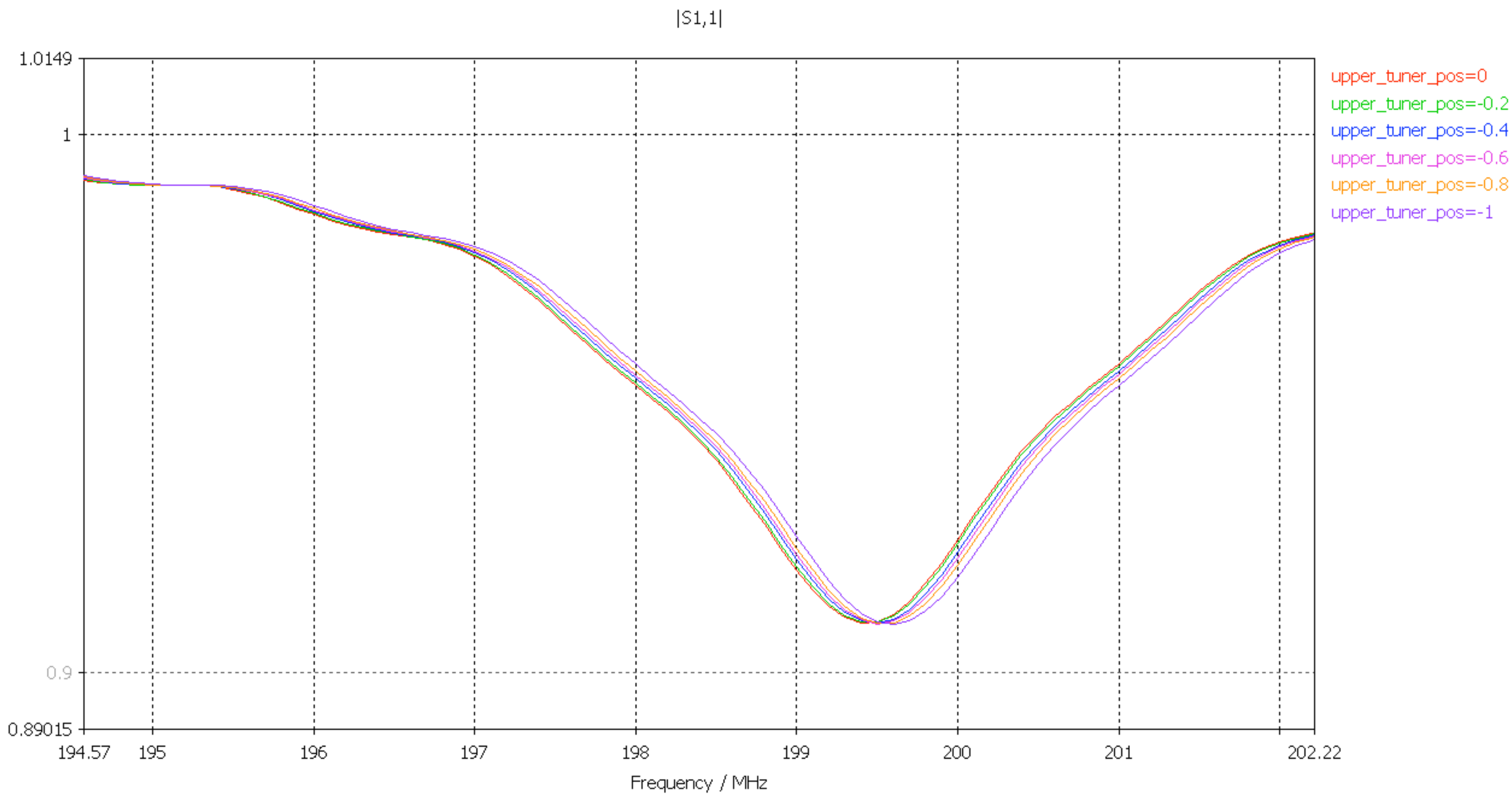
• Eccosorb MF124 absorber blocks, high magnetic loss
• Inside reduced height waveguides to minimize 200 MHz being below cutoff
• Upper and lower locations effective

2011 Simulations using CST Microwave Studio

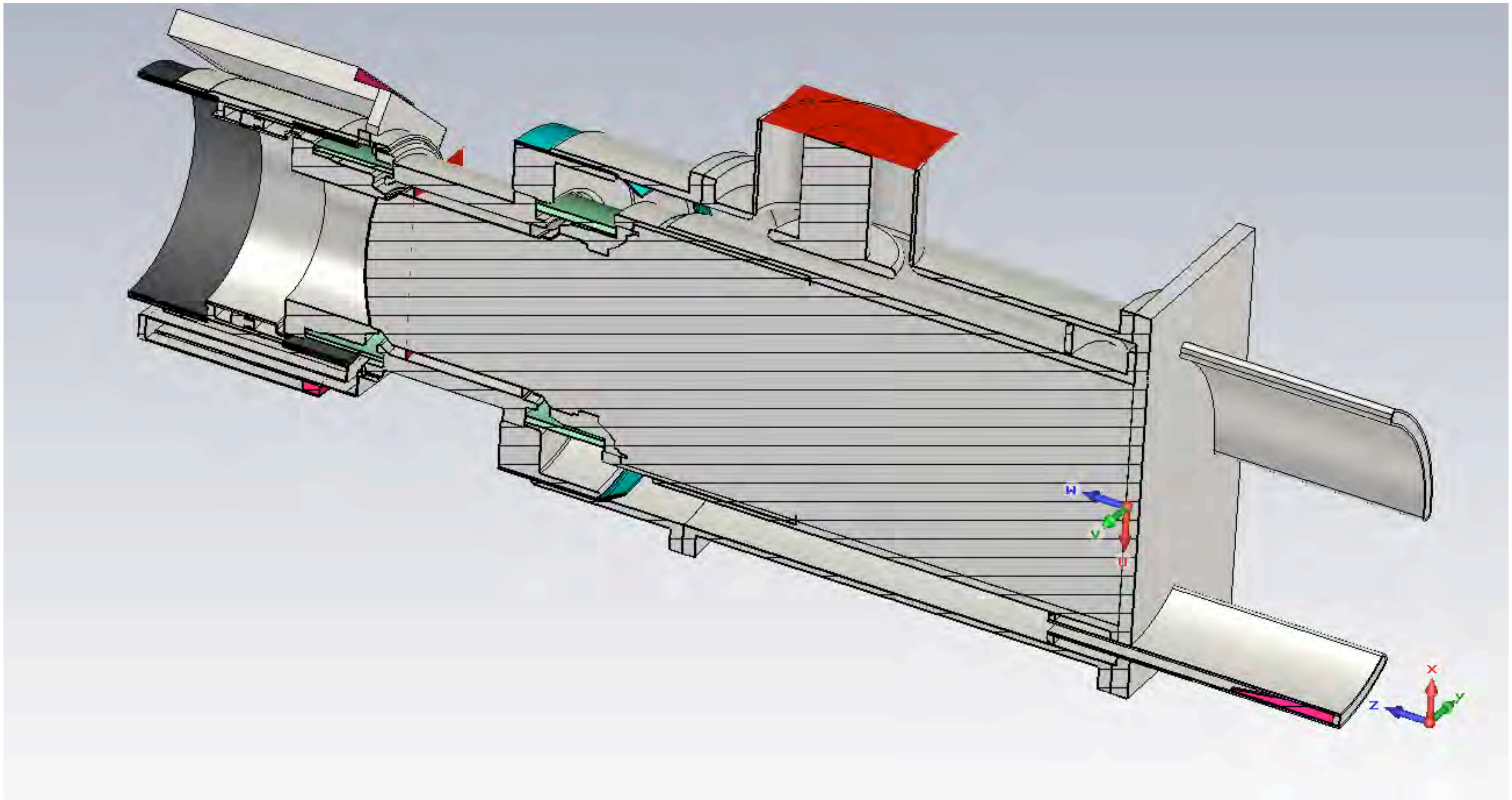




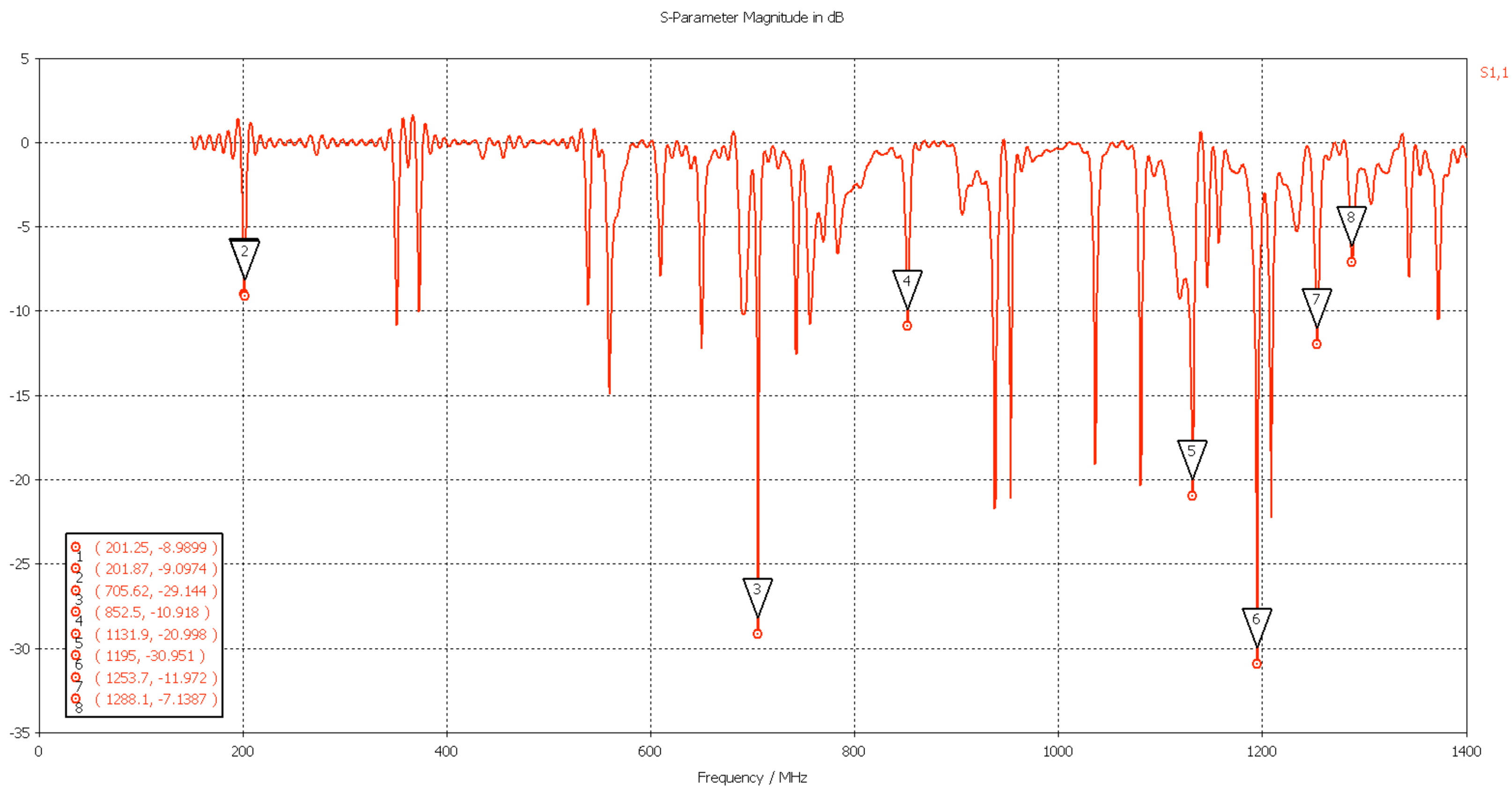
CST - Parameterized Main Tuner



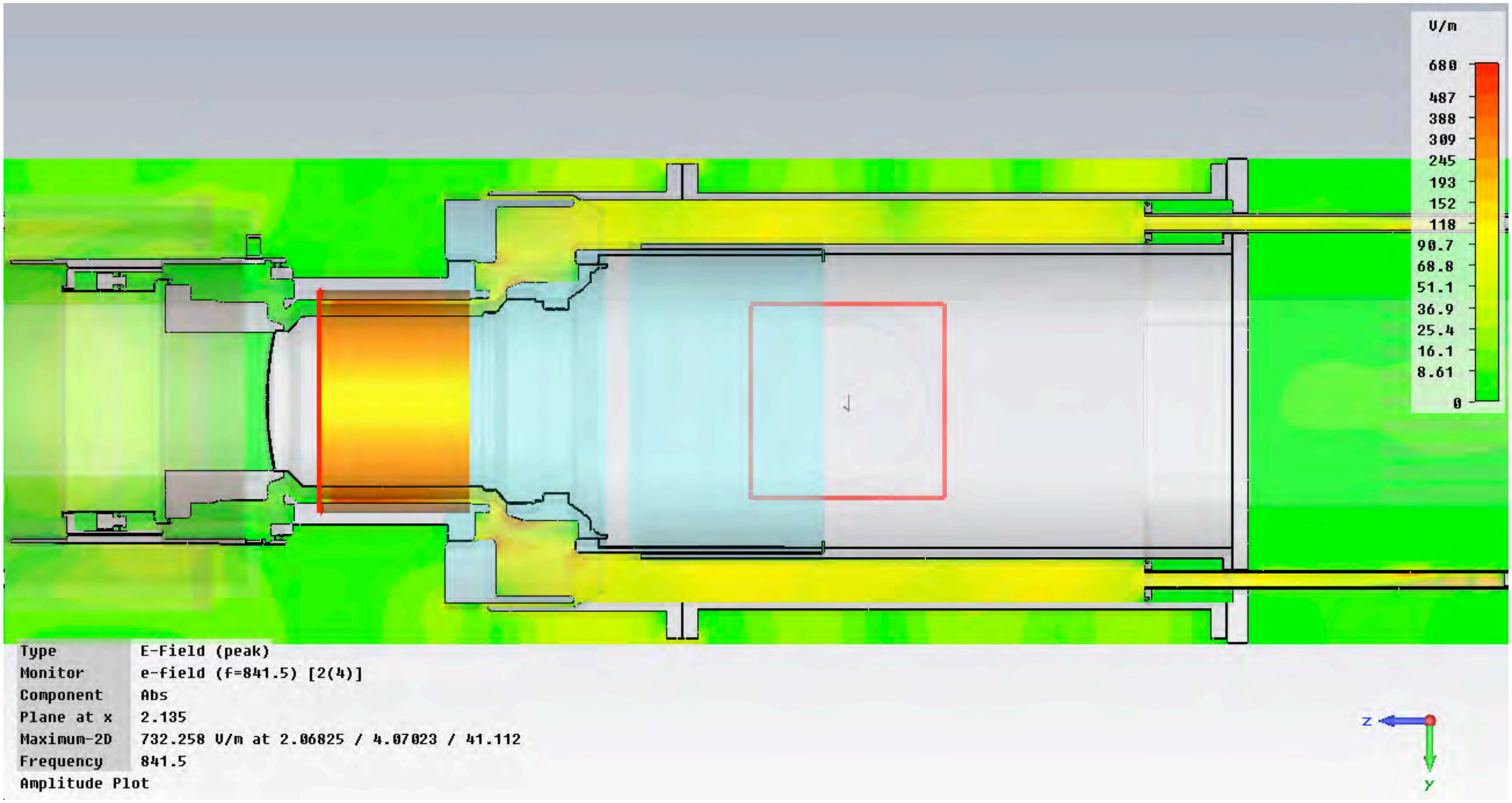
Excitation Ports for Various Resonances



Initial Results



Field Plot Showing TE_{21}



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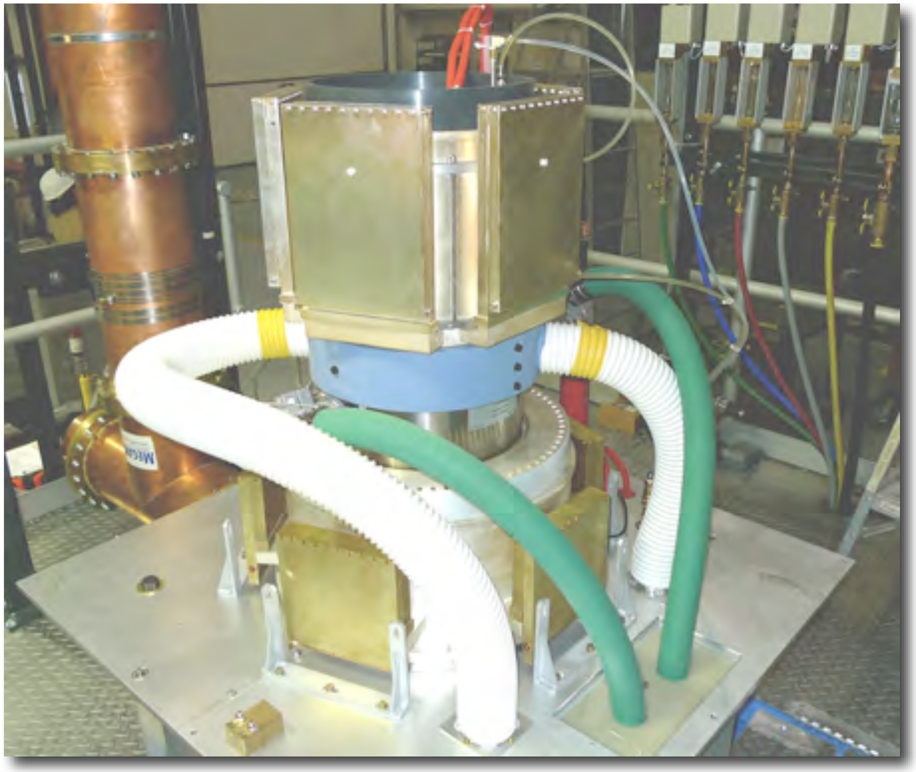
Testing

TH628 Ready to Install

TH628 Power Amplifier



Air and water cooling hoses

Safety Enclosure

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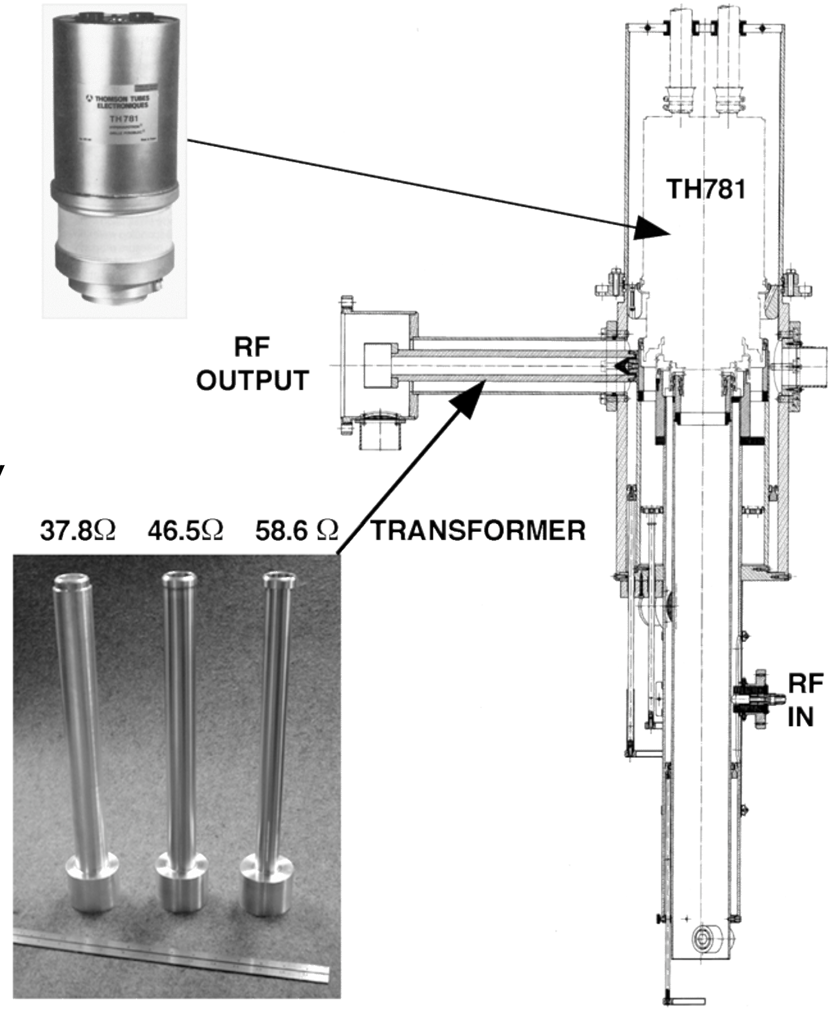
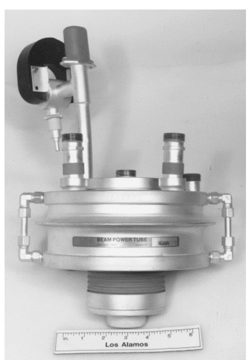
FPA on left, IPA on right

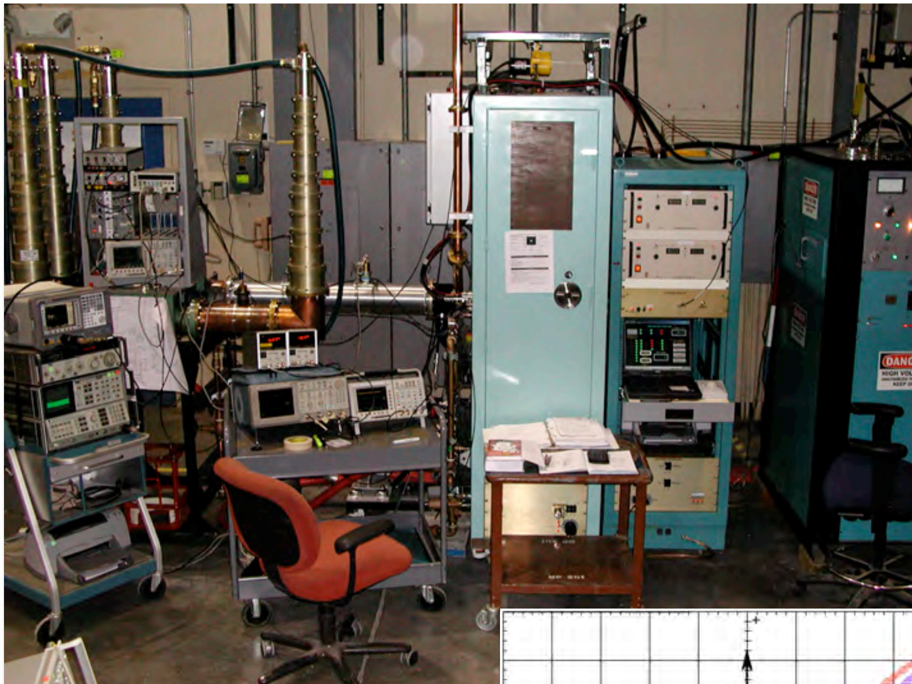
Intermediate Power Amplifier

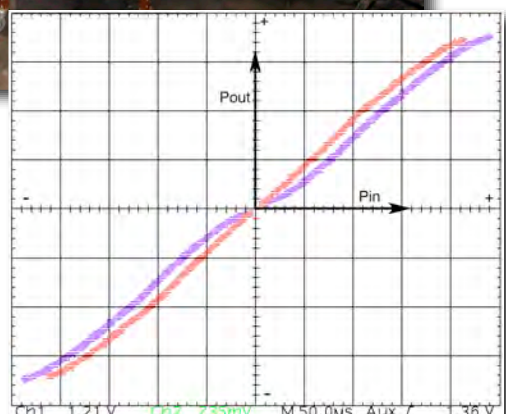
- Uses commercial PA cavity
- Thales TH781 tetrode
- Complete system, 50“ Width
- Reuses 4616 anode power supply
- Replaces Burle 4616 tetrode, due to insufficient avg. power

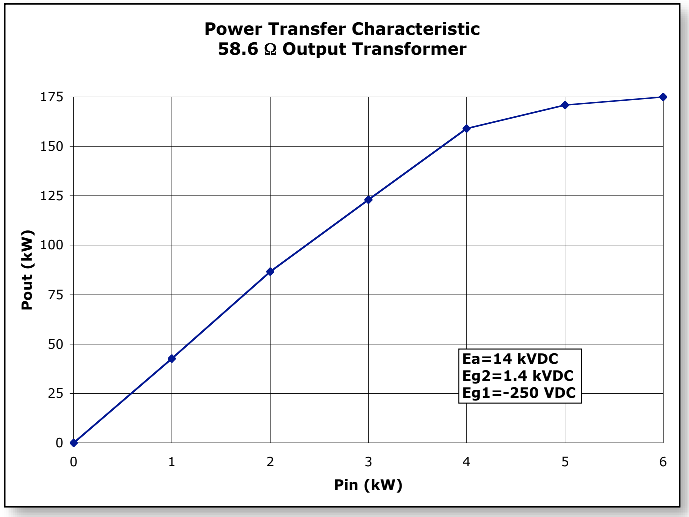


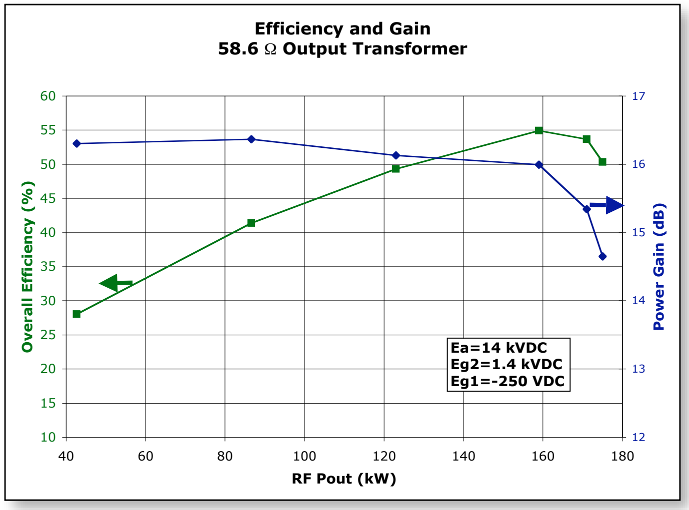


Intermediate Power Amplifier









Prototype
Tested in 2004

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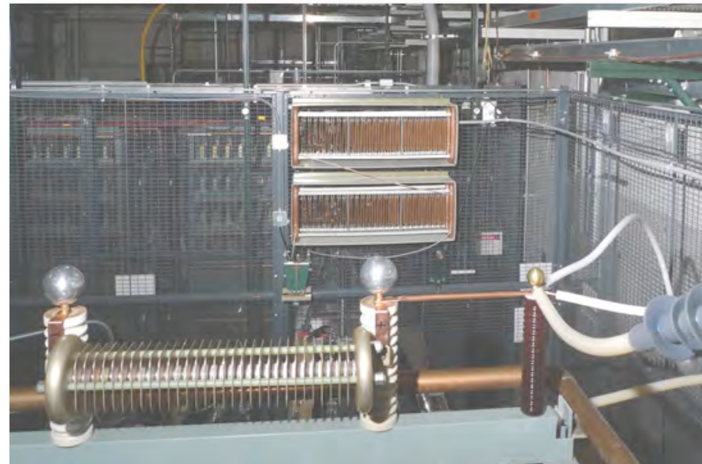
TH781 Sockets, Besides LANL

- CERN (40 and 80 MHz Buncher in PS)
- IBA in E-Beam Sterilization Machines
- Debeers (Diamonds) in South Africa
- IFMIF/EVEDA linac, 175 MHz, 18 systems
- 200 MHz RFQ in development, IHIP, Beijing

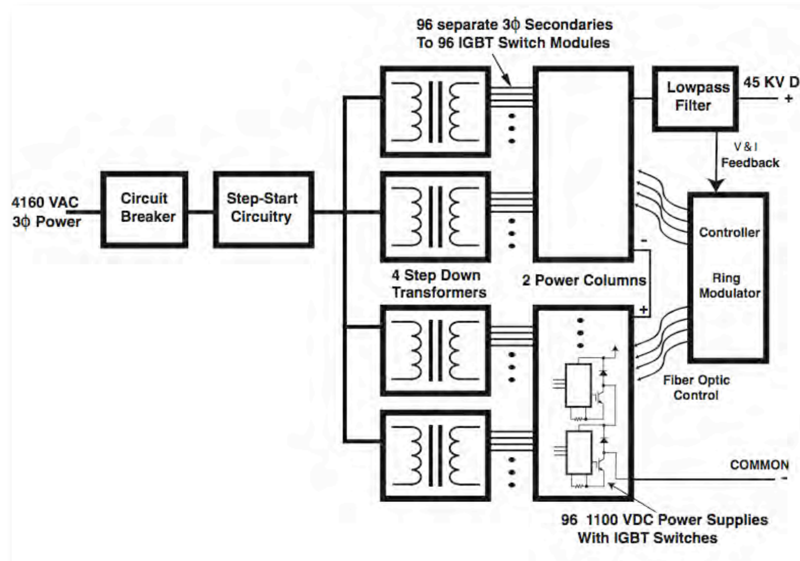
Overall View of New Test Set

Capacitor Bank on Right

Charging Power Supply



Isolation diode and static load



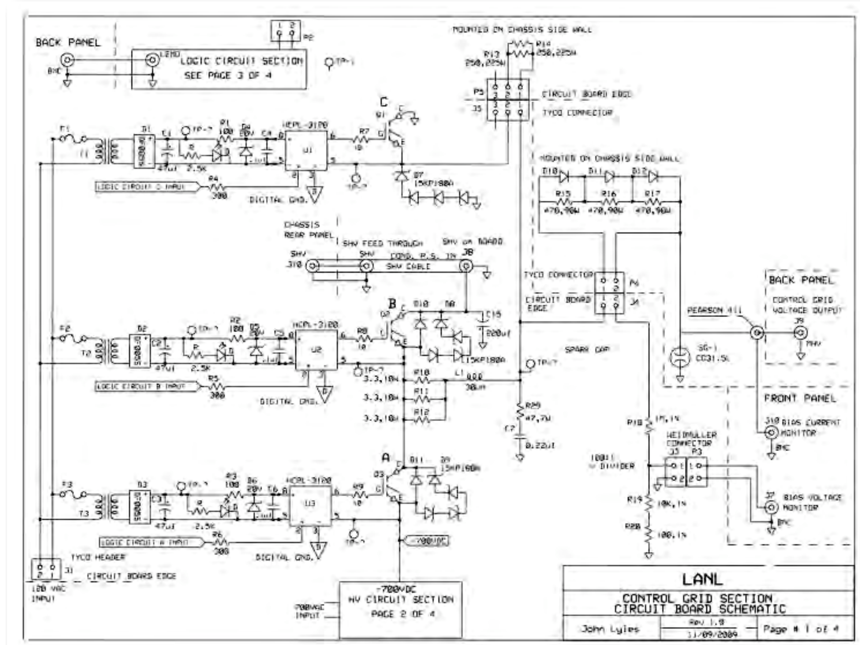
Capacitor Bank, 88 kJ, 225 uF

Crowbar on right side

Water Cooling Manifold

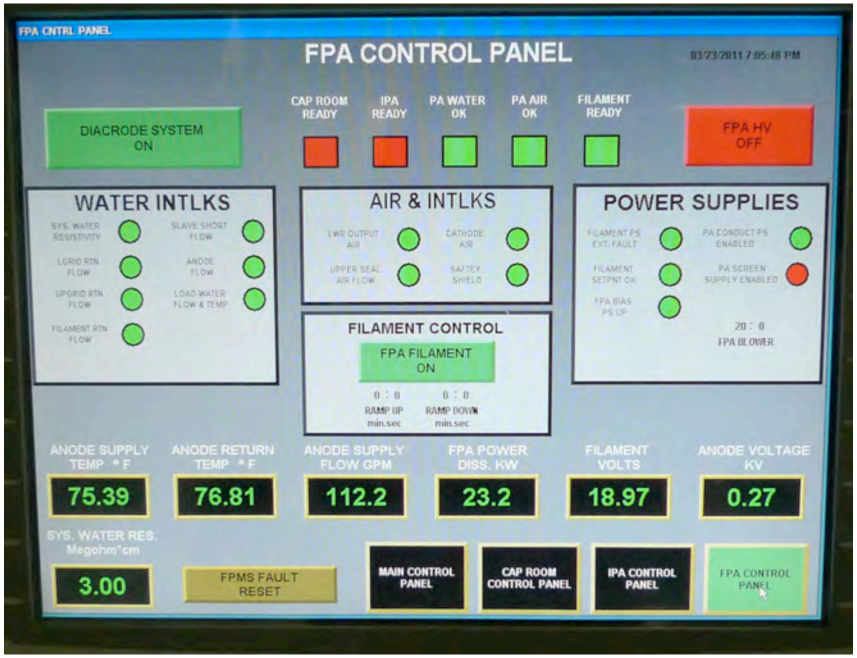
Ionized Water Column RF Load

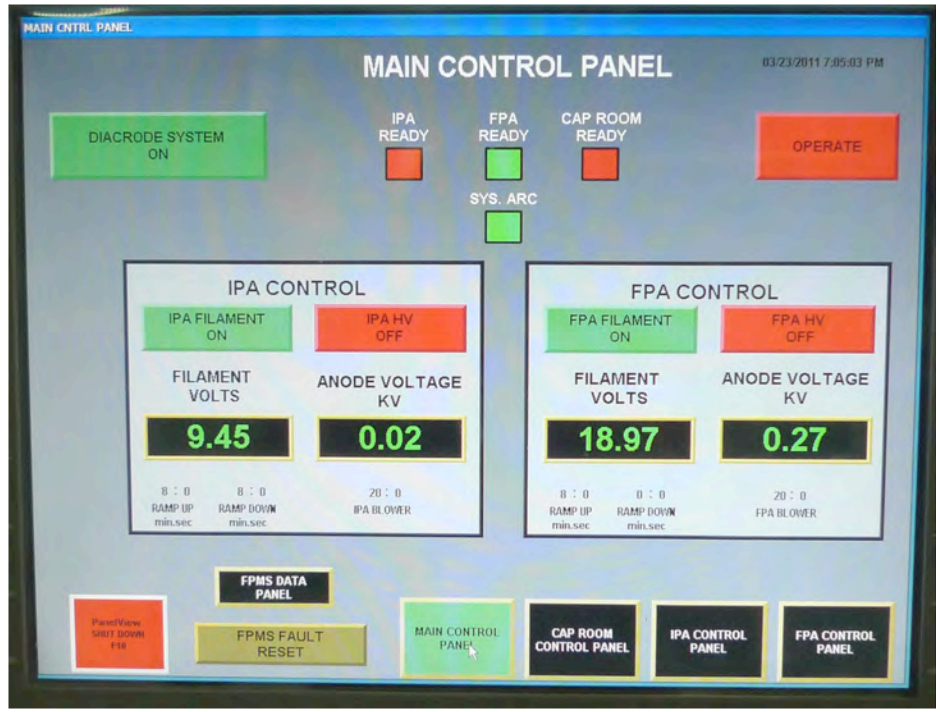
Modulators for Power Amplifiers



- Low stored energy power supplies
- IGBT switching between cutoff and conduction bias (-340 VDC) on control grid (-250 for TH781)

Programmable Logic Controller





For cooling protection, power supply sequencing, interlocks, GUI

FPMS

For fast protection from reflected power, excessive currents, HV, including RF power metering

Power Amplifier Test Summary

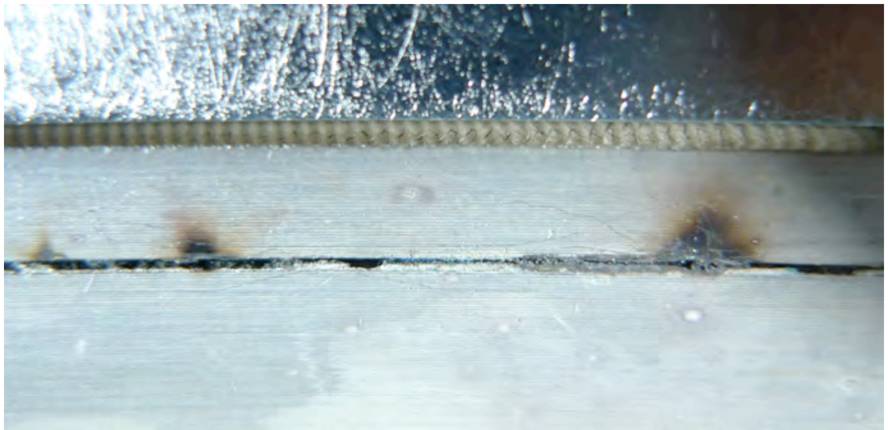
- Oct. - Nov. 2010
  - Testing at Low DF (<0.5%) and high peak power, to determine tuning response, basic operating parameters, troubleshoot test stand interlocks, power supplies and controls, calibrate instrumentation, and incorporate safety improvements
  - Basic amplifier design proven with 2 MW peak, with evidence of intermittent TE_{31} high order mode and operating at 198 MHz due to input circuit limitation
  - Thales engineer visited for week, provided assistance working through solutions
  - Defective diodes in screen grid bleeder assembly caused much trouble, replaced
  - G_2 spark gap sizing caused delays until modified

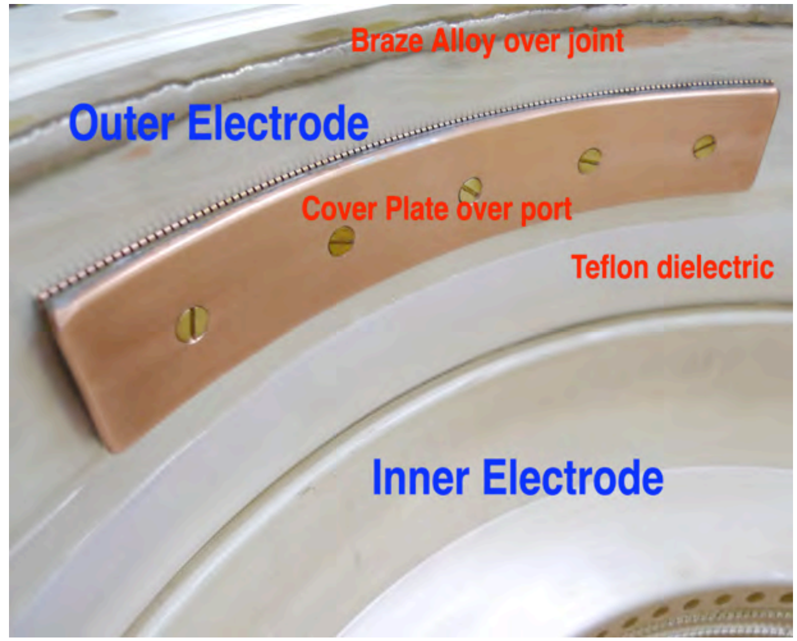
Power Amplifier Test Summary

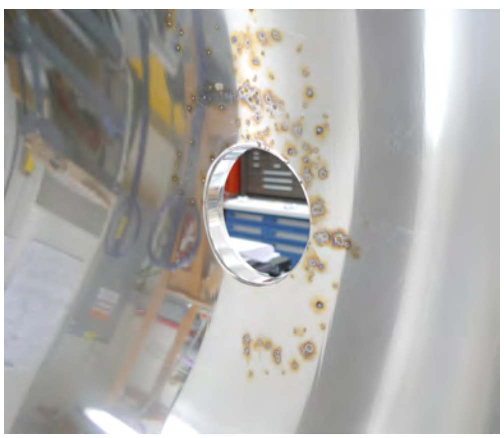
- **Dec. 23 - Jan. 14: REV1, 16 modifications installed, 3 major tasks**
  - **Modeled and revised input circuit with aluminum sleeve to center operation at 201 MHz**
  - **Closed off (5) HOM waveguide damper slots in lower anode blocking capacitor assembly**
  - **Removed output cavity, G_2 resonator, support plate and returned to PF main shop for rework to accommodate waveguide penetrations**
  - **Designed and fabricated (3) new adjustable waveguide dampers using EDM, modified main tuning ring**
  - **Numerous smaller improvements, tuning rods, RTDs installed, new air switches**
- **Jan. 14**
  - **testing of rebuilt amplifier reveals arcing around old waveguide slots**
  - **Inspection reveals partially open horizontal seam at flange joint of lower blocking capacitor assembly**

High Power RF is Unforgiving

Attention to Every Detail is Essential







Power Amplifier Test Summary

- Jan. 17- Feb. 23: REV2, modifications to eliminate RF current going in joints
  - Curved cover plates with contact fingers for old waveguide slots
  - Silver alloy applied over horizontal seam using braze technique
- March 1 - 4: peak (2.5 MW) and average (102 kW) power testing
  - Water load connection and window fail catastrophically (2.5 weeks downtime)
- March 29 - April 7
  - Testing revealed RF sparking across air inlet screen to G_2 resonator
  - Main tuner arcing heard
- April 11 - May 4: REV3, modifications to tuner, redesign of air inlet screens, waveguide modifications to reduce harmonic heating, AFT arc detector installed but not working

Power Amplifier Test Summary

- May 9 -13
  - Testing 2 MW up to 9% DF
- May 16-19
  - Modified LAMPF accoustic arc detector for fast response, installed on water load and FPA cavity
- May 23 - 27: Continued testing except for downtime due to:
  - Flow switch failures and replacements (2)
  - Filament power supply trips, modified with relays to remove problem
- May 28-31: Endurance run at 2 MW peak, 12% DF, 240 kW average
  - 80 hours continuous operation
  - No trips due to RF, heating, or stability

Power Amplifier Test Summary

- June - August : Various runs at 2 and 2.5 MW peak, 10 and 12% DF
    - Testing to validate final dimensions for a few detail drawings, to prepare for production release
    - Modifications to add air into output coupler, coax
    - Testing of new Mega 9 inch water load
    - Troubleshooting IPA anode power supply
- Cumulative operating time on Thales tubes

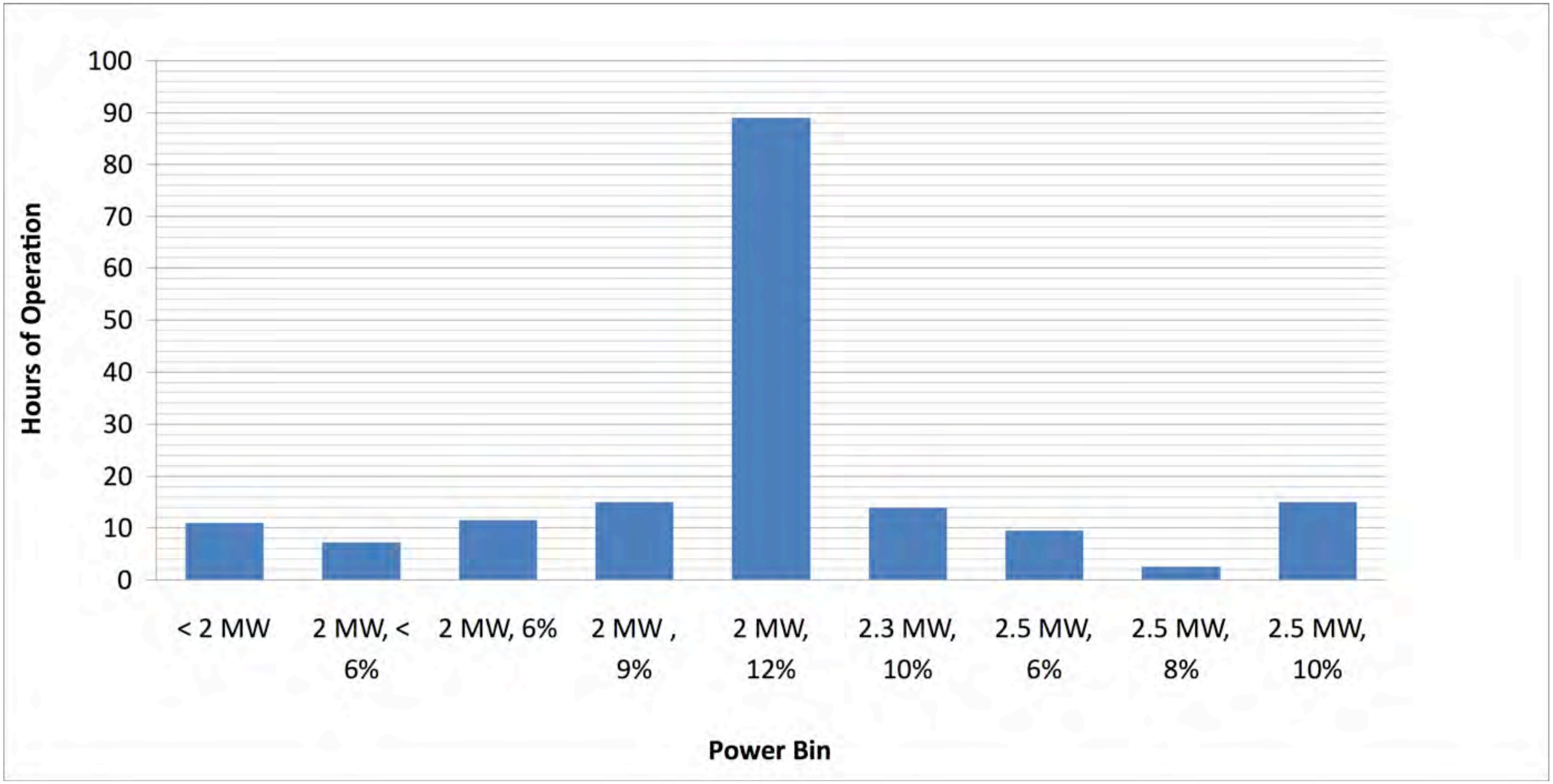
    TH628 Diacrode

    - Filament 966 hours
    - HV 257 hours

    TH781 Tetrode

    - Filament 2405 hours

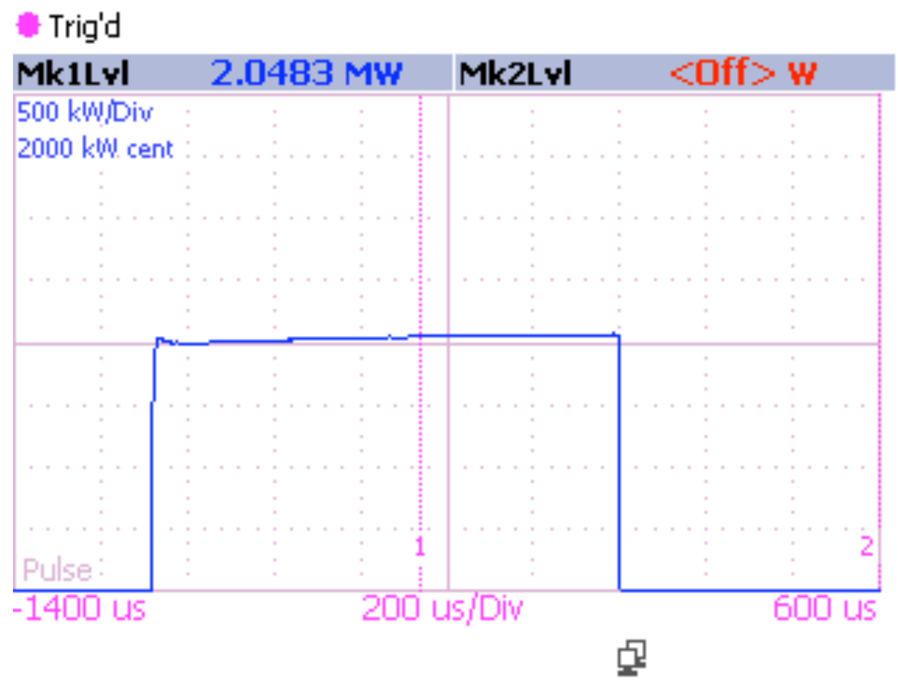
Summary of Test Experience



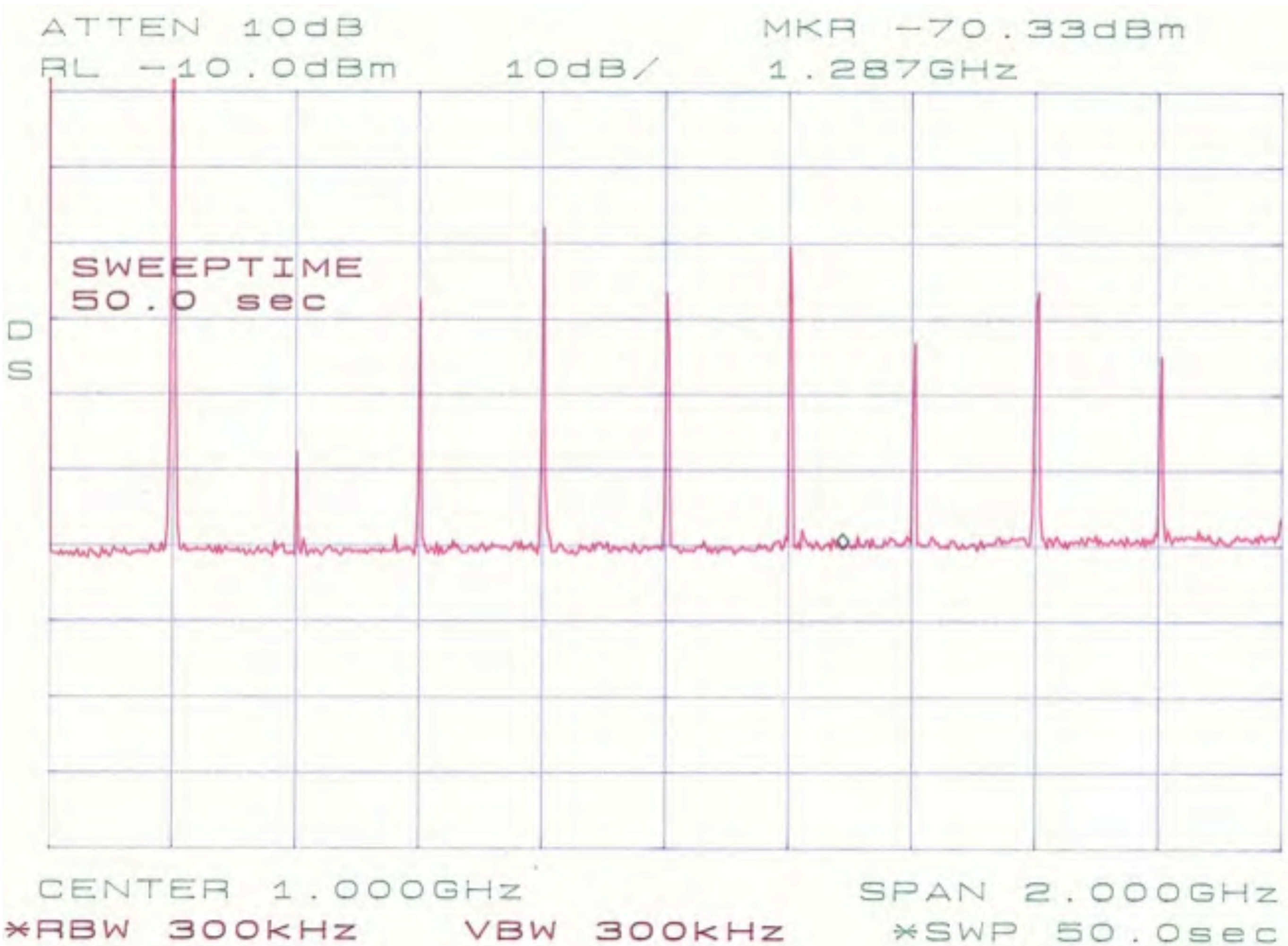
As of August 22, 2011

Highlights of Test Results to Date

Ea (kV)	Ia (A)	Eg2 (kV)	Ig2 (A)	Eg1 (V)	Pin (kW)	Pout (MW)
			Pulse	**=**	**1.08mS**	**120pps**
26	111	1.54	3.72	-340	59	2
27	110	1.54	3.42	-340	62	2
			Pulse	**=**	**835 uS**	**120pps**
28.3	124	1.54	4.2	-340	76	2.5



Power Spectrum at Output

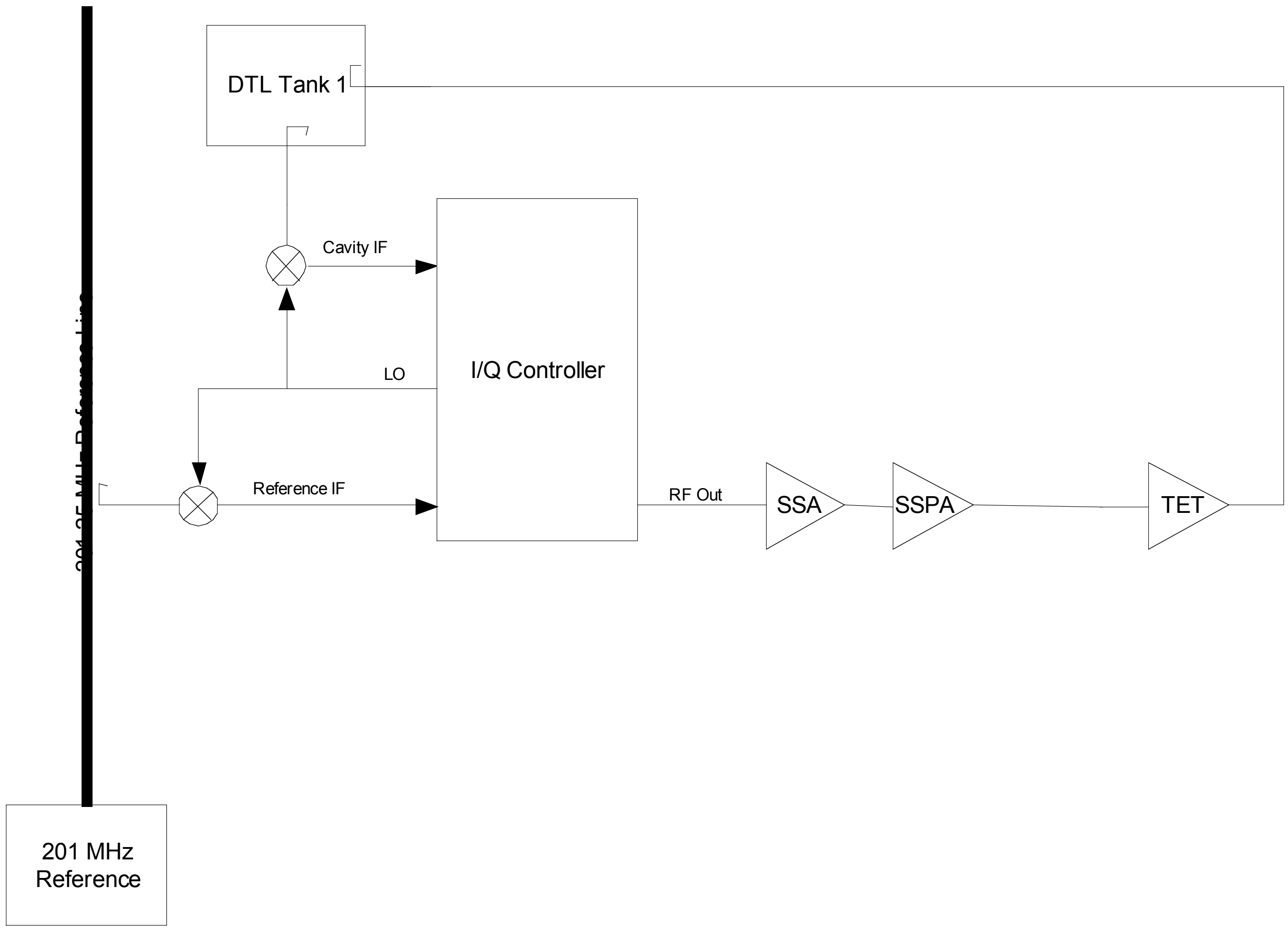


Installation Details

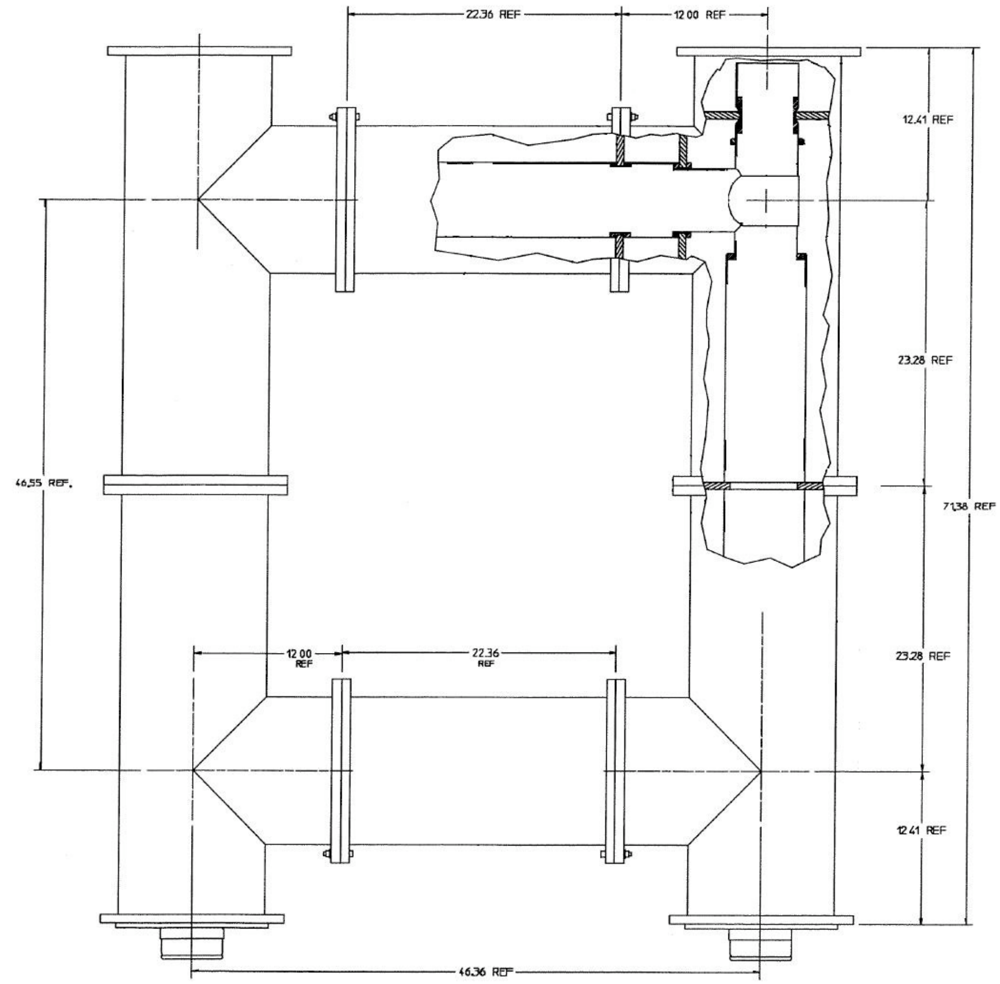
LLRF Controller (for DTL)

- Digital I/Q Controller with Direct Control of the Low Level RF Drive to Amplifiers
- Down Convert Both Reference and DTL Samples to Common IF To Reduce Transport Errors
- FPGA-Based Controllers for PID
- Modifies Set Points on a Pulse-to-Pulse Basis
- Adaptive Feed Forward Learns and Improves on Beam Losses for Each Beam (up to 8)

RF Control Scheme



Coaxial Power Combiner



Coaxial Branch Line Hybrid from Mega Industries

Los Alamos NATIONAL LABORATORY EST. 1943

UNCLASSIFIED

LANSCE Los Alamos Neutron Science Center

Power Combiner Examples

Branch Line Hybrid is Conservative Design

- BNL for AGS Linac, Dual Feeds to DTL tanks
- Kwajalein VHF Radar (Altair) Combine 2 4617 PAs

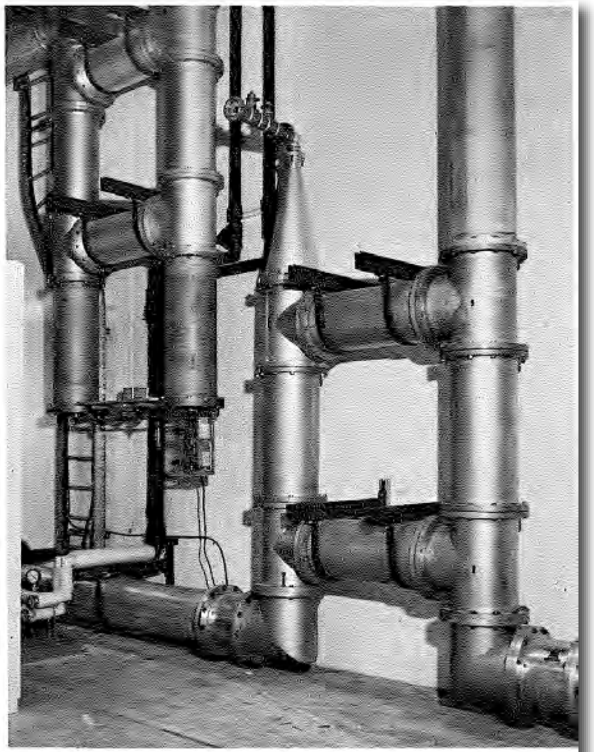
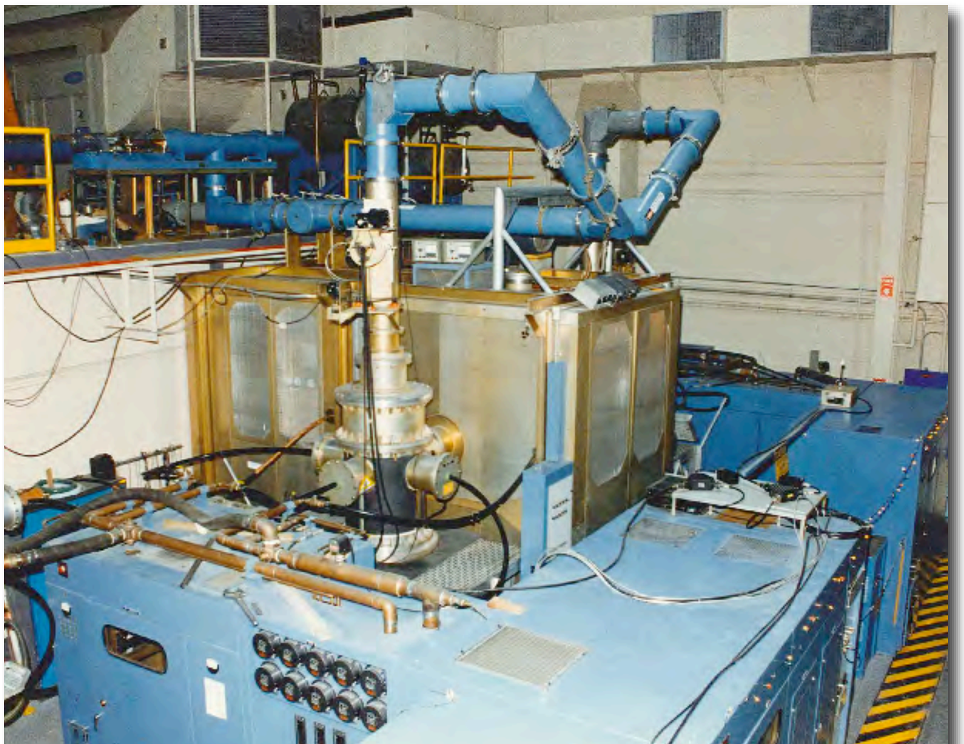
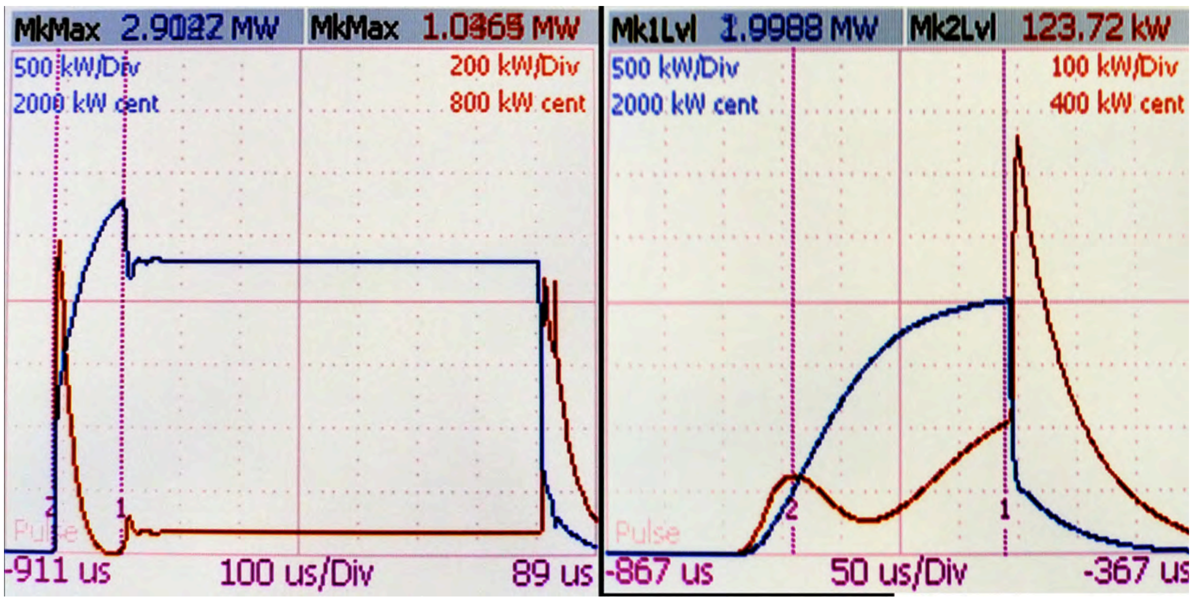


Photo from J. Keane, PAC 1972



Eliminated Circulator from Baseline Design

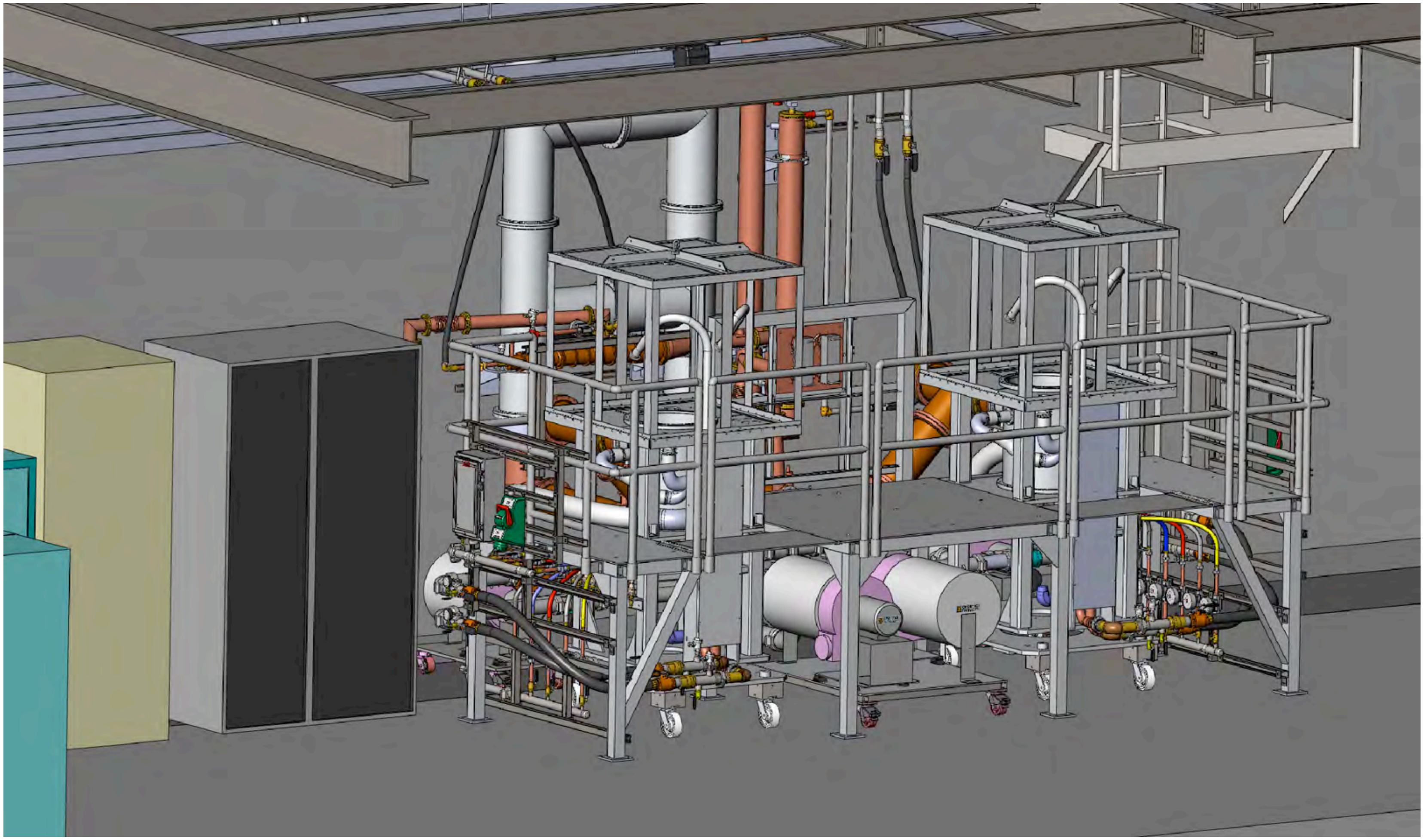
- Have partially tested 14 inch AFT circulator in house using 7835, needs additional work
- Testing ramped RF through 7835/modulator, transient reflected power reduced from >1 MW to <130 kW peak
- Contingency planning includes location, coax and water design



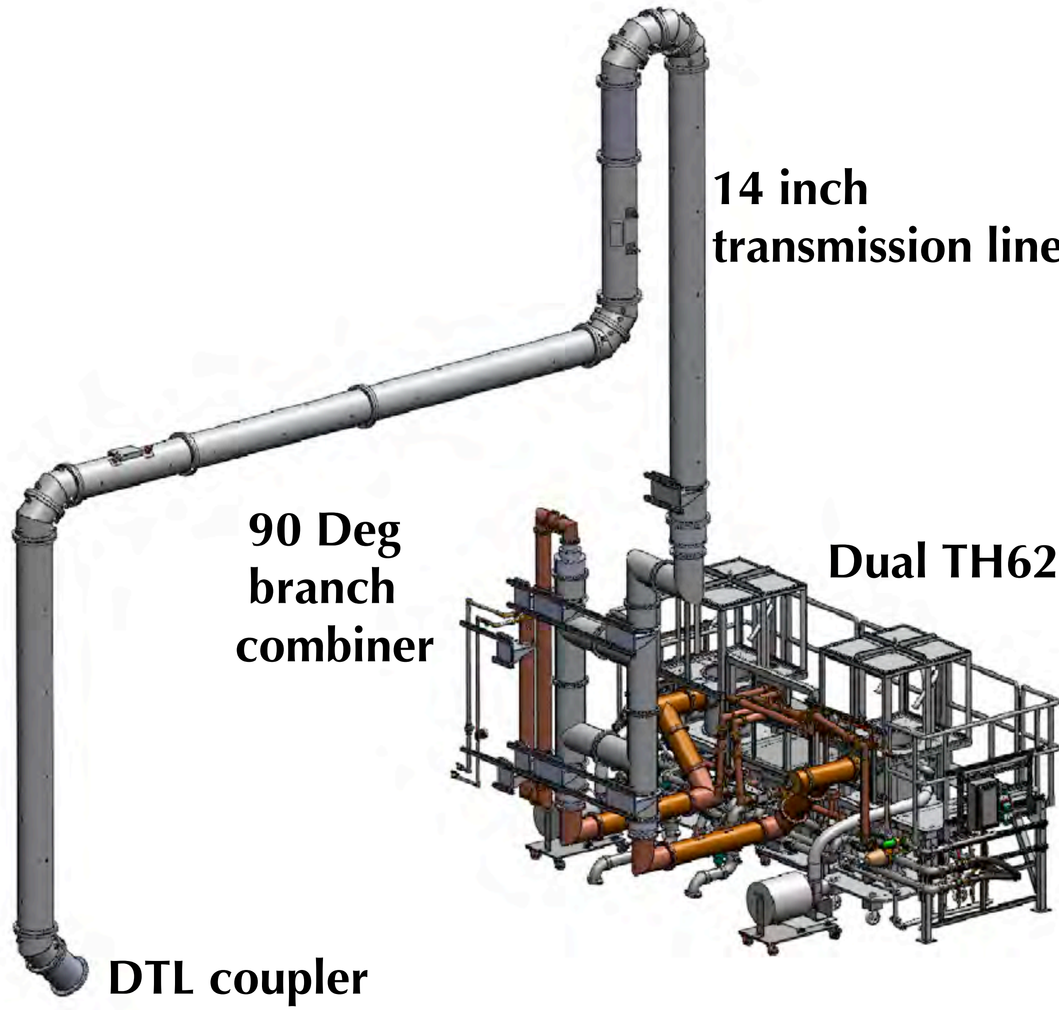
Present Layout of Modules 2, 3 and 4

- Everything Shown (Except IPA Power Supply) To Be Removed
- Much Legacy Wiring and Plumbing to Remove
- All 480VAC in Racks will be Removed

Layout for Dual Amplifier Station



Coax Layout to DTL



Summary of Schedule

- Prototyping testing complete, now life testing
- Subsystem production underway for electronics
- FPA fabrication ready for bidding,
  - Oct-Dec. 2011
  - Build-to-print, over 300 drawings
- IPA fabrication few months from ready for RFQ
  - Some GFE material purchased or on-hand
- First combiner, load, splitter, phase trimmer purchased, delivery in Nov. 2011
- Power Supplies for G1, G2, filaments purchased
- Major tube purchases underway

Summary of Schedule

- Wiring identification and planning underway
- Amplifier and tube delivery and testing in late 2012
- Installation of electrical utility additions 2012
- Installation of major coaxial components in 2012
  - For second FPA
  - Circulator contingency planning
- Installation of dual amplifier for tank 2 in 2013
- Operation with hybrid system into 2014, select 7835s for highest average power for tanks 3-4
- Installation of remaining 2 systems, one per year

Diacrode Development Team

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Questions?
DANGER
HIGH VOLTAGE